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Timing and metastability in synchronous circuits

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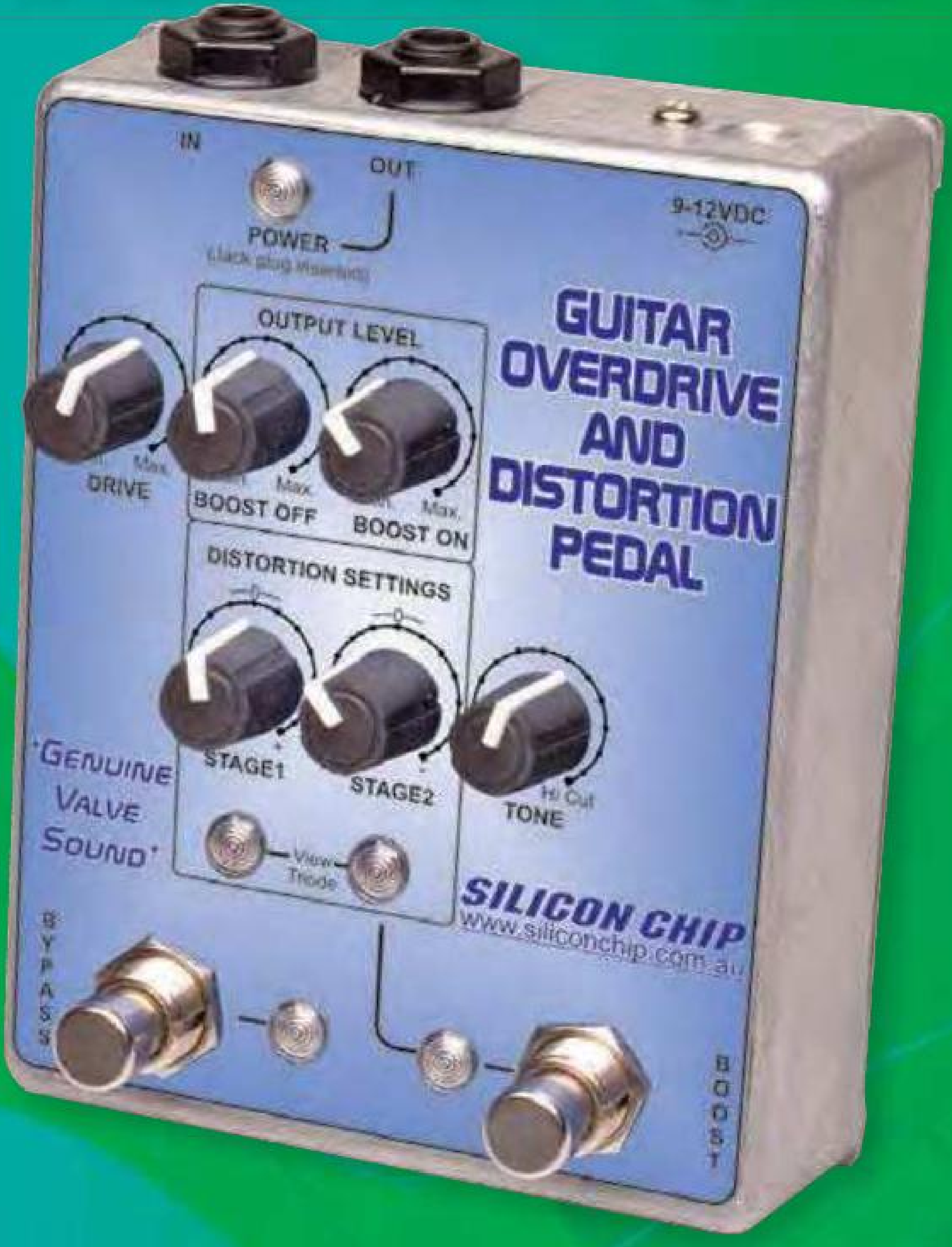
Fun display project using a Micromite Plus

Audio Out
How to make a transistor radio

Nutube Guitar Overdrive and Distortion Pedal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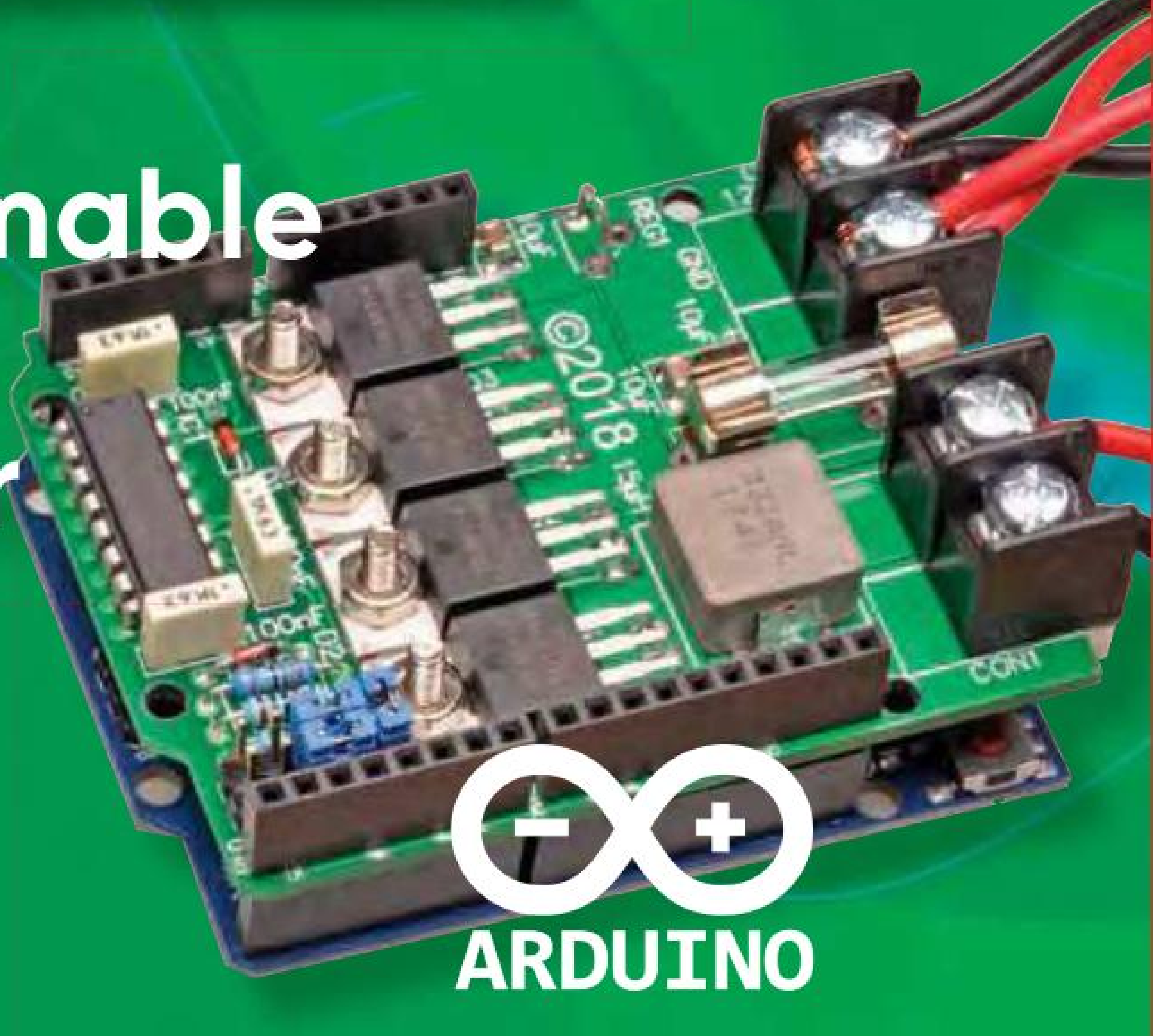

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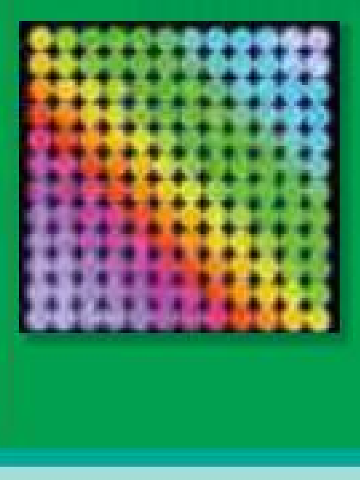

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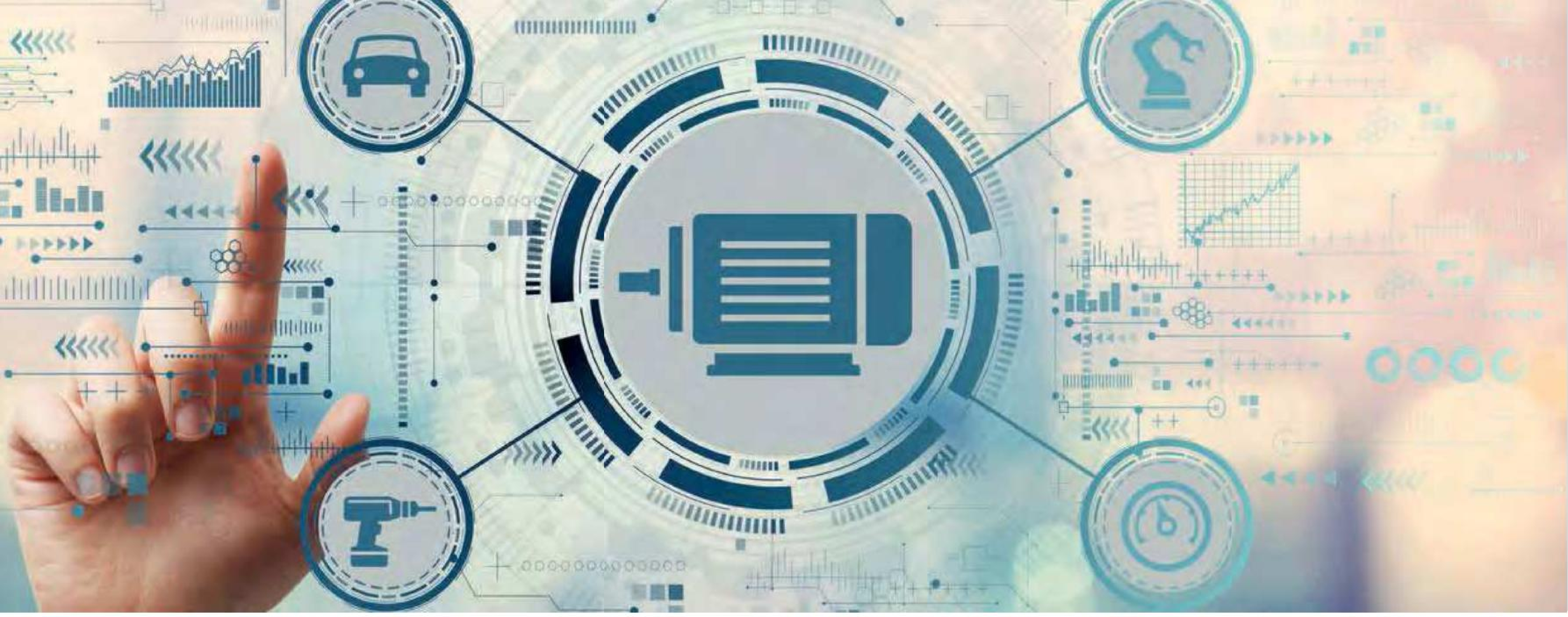

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The April 2021 issue of *Practical Electronics* will be published on Thursday, 4 March 2021 – see page 72.

WIRELESS FOR THE WARRIOR

by LOUIS MEULSTEE

THE DEFINITIVE TECHNICAL HISTORY OF RADIO COMMUNICATION EQUIPMENT IN THE BRITISH ARMY

The *Wireless for the Warrior* books are a source of reference for the history and development of radio communication equipment used by the British Army from the very early days of wireless up to the 1960s.

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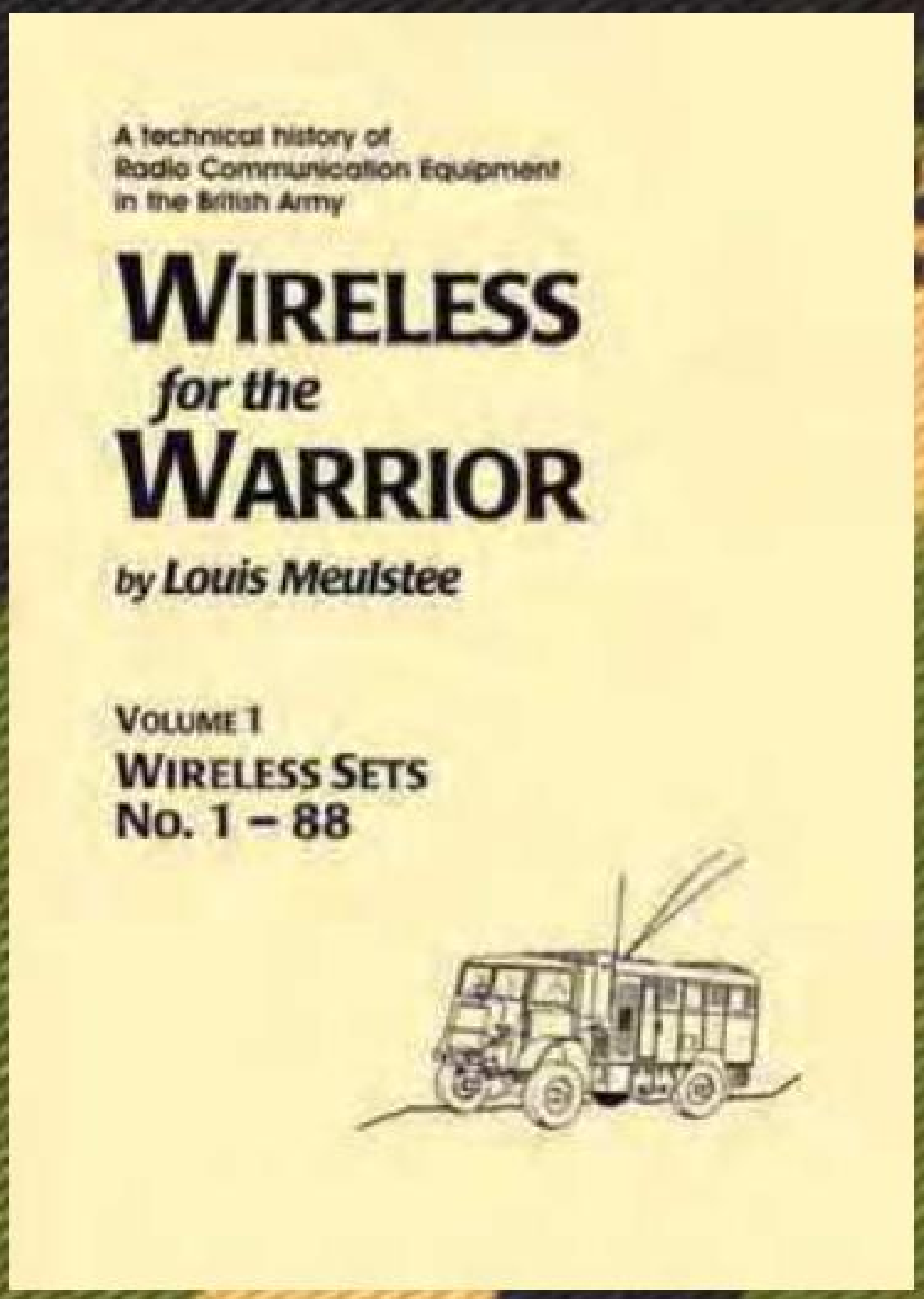
Volume 1 and *Volume 2* cover transmitters and transceivers used between 1932-1948. An era that starts with positive steps taken to formulate and develop a new series of wireless sets that offered great improvements over obsolete World War I pattern equipment. The other end of this timeframe saw the introduction of VHF FM and hermetically sealed equipment.

Volume 3 covers army receivers from 1932 to the late 1960s. The book not only describes receivers specifically designed for the British Army, but also the Royal Navy and RAF. Also covered: special receivers, direction finding receivers, Canadian and Australian Army receivers, commercial receivers adopted by the Army, and Army Welfare broadcast receivers.

Volume 4 covers clandestine, agent or 'spy' radio equipment, sets which were used by special forces, partisans, resistance, 'stay behind' organisations, Australian Coast Watchers and the diplomatic service. Plus, selected associated power sources, RDF and intercept receivers, bugs and radar beacons.



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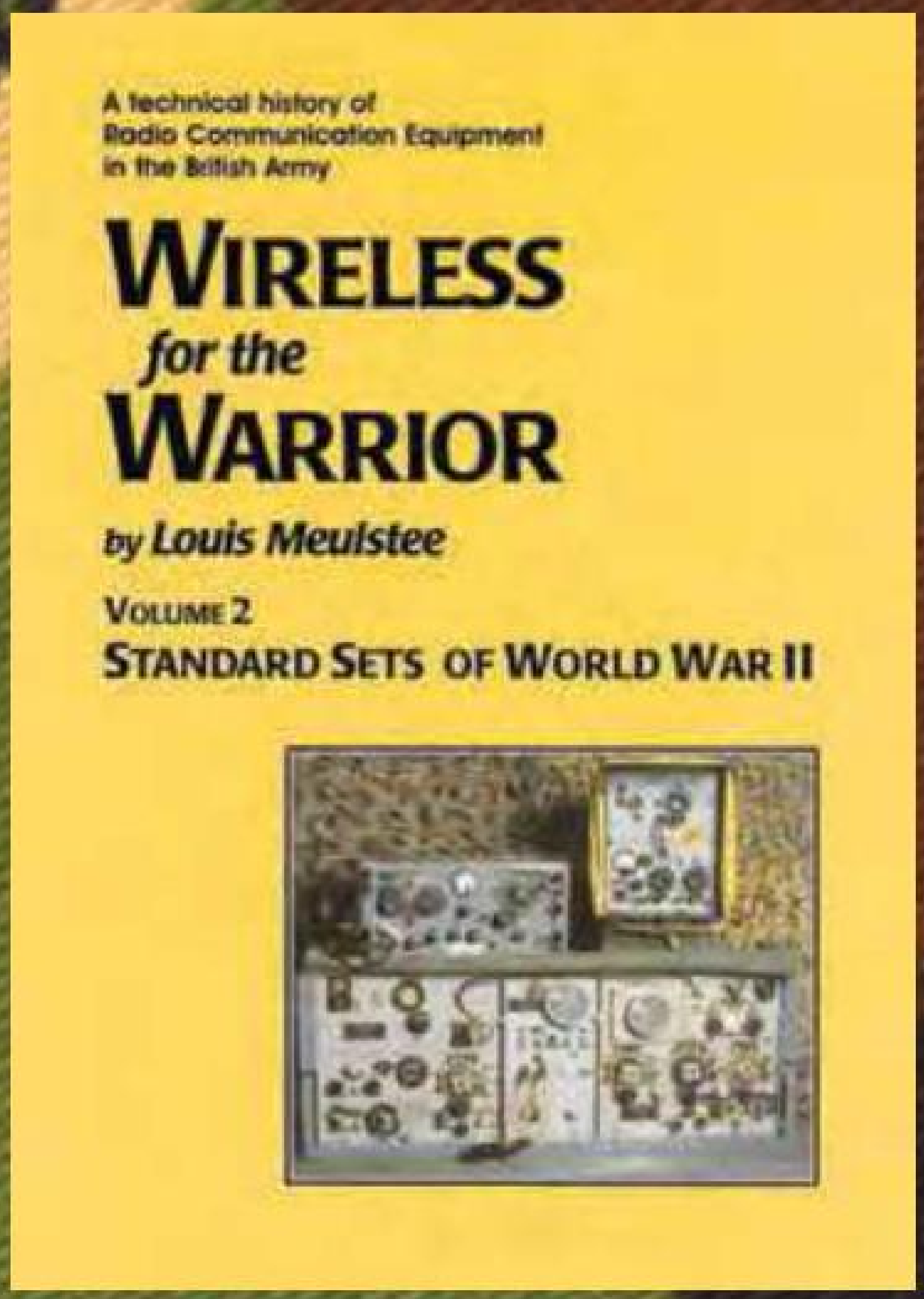

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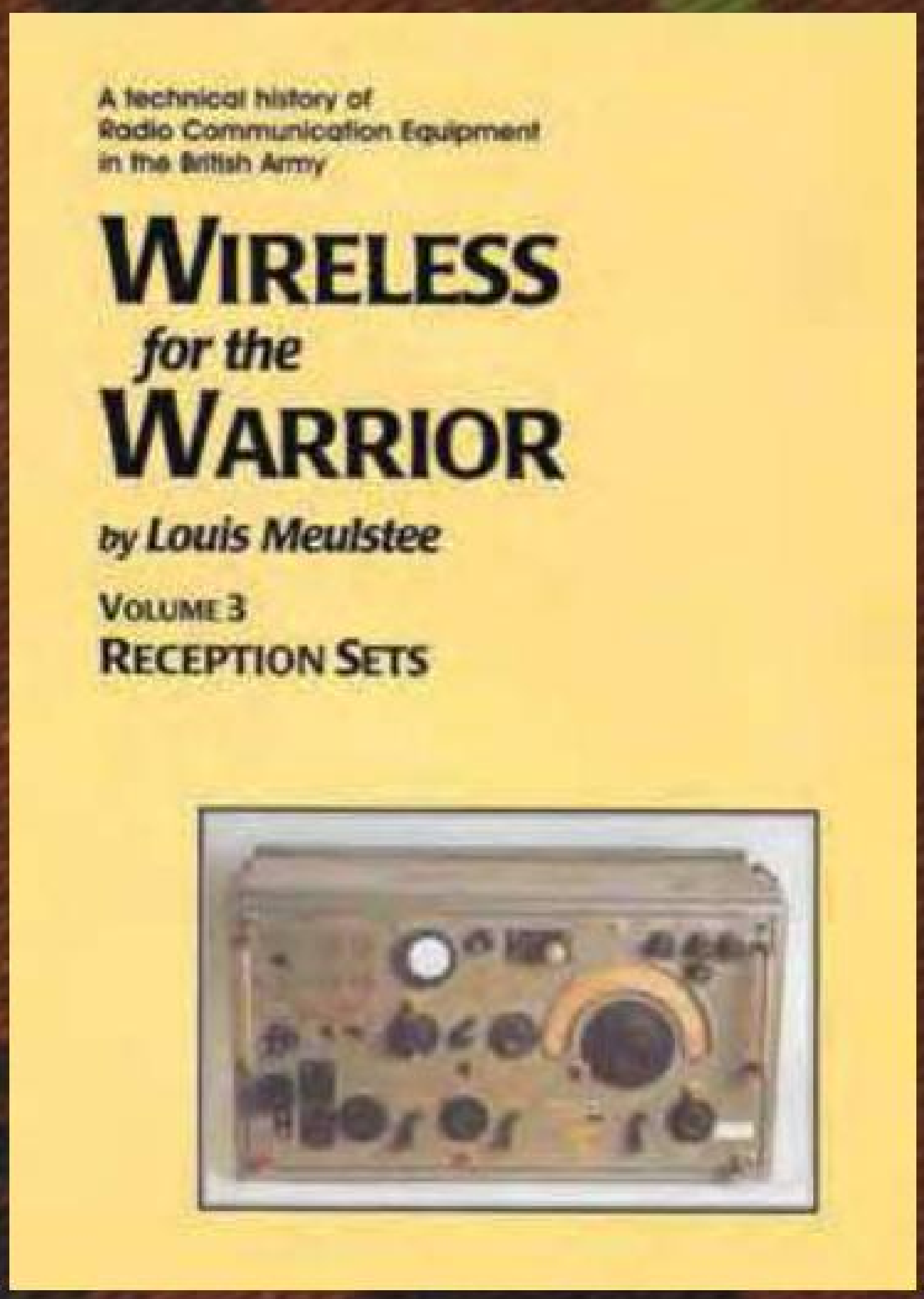

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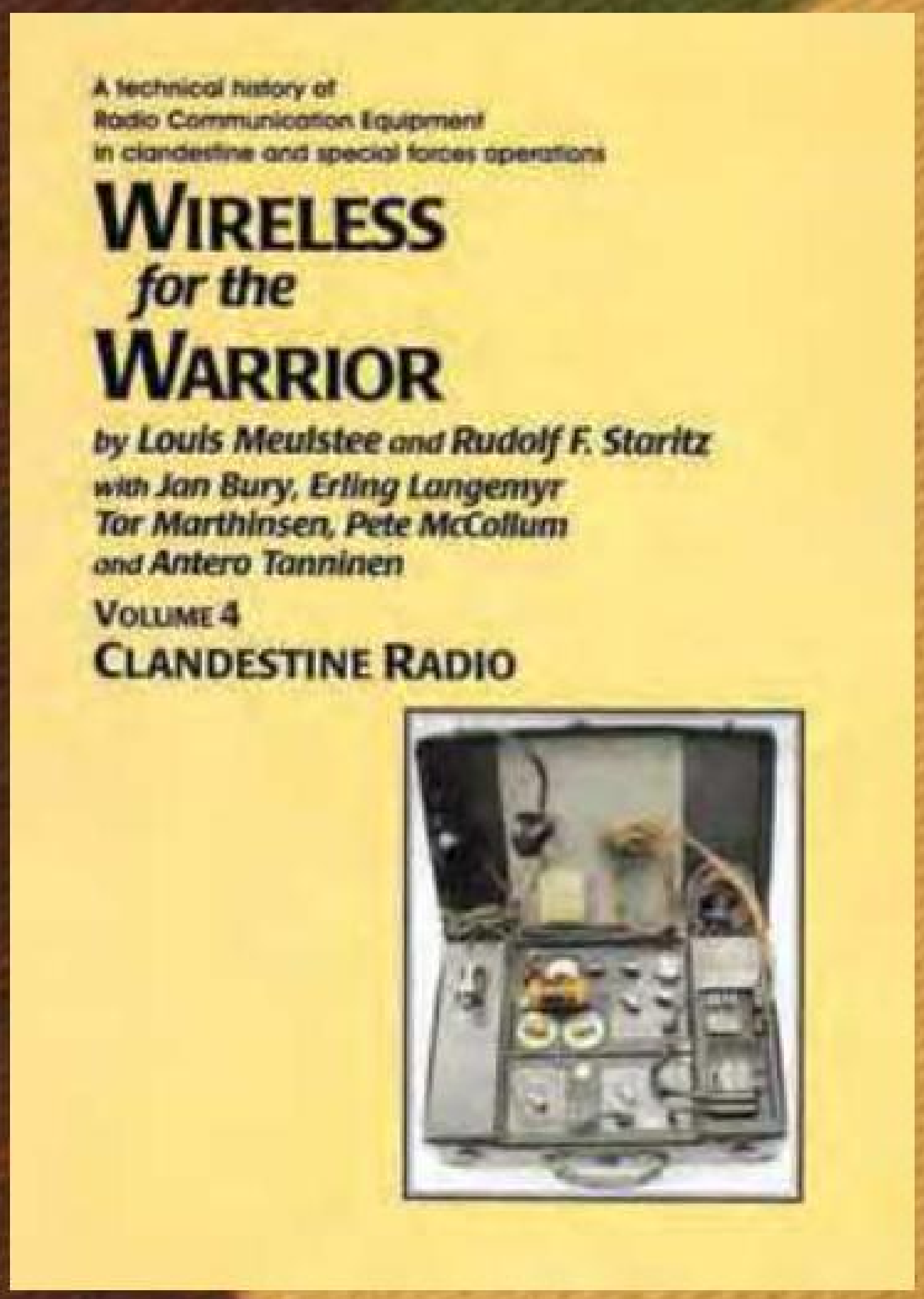

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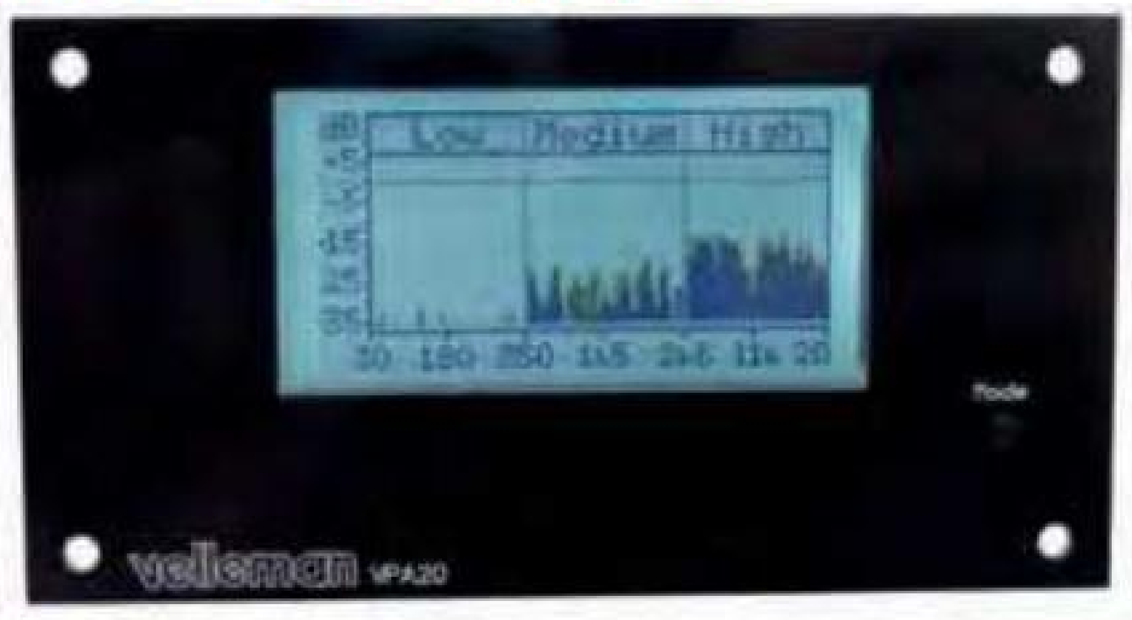

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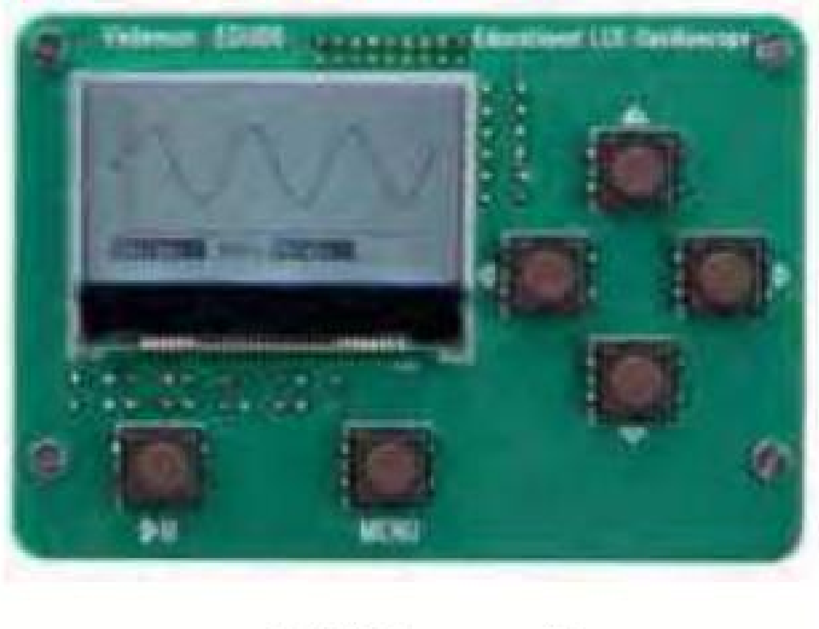

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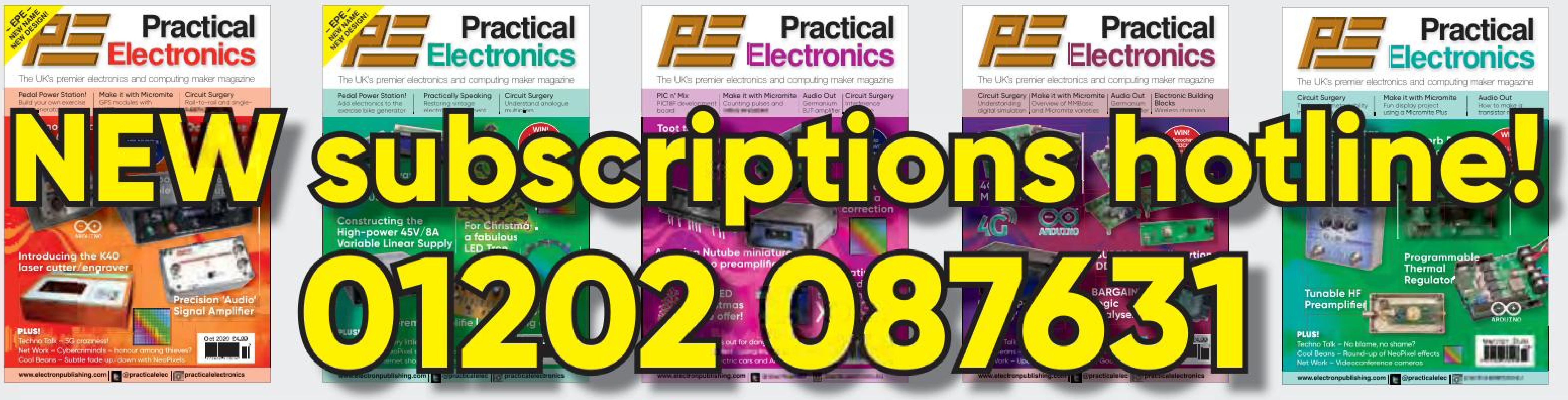

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All reasonable precautions are taken to ensure that the advice and data given to readers is reliable. We cannot, however, guarantee it and we cannot accept legal responsibility for it.

A number of projects and circuits published in *Practical Electronics* employ voltages that can be lethal. You should not build, test, modify or renovate any item of mains-powered equipment unless you fully understand the safety aspects involved and you use an RCD (GFCI) adaptor.

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Worth the wait...

Some projects come to us as fully formed ideas – we look at them and can quickly say ‘yes’ or ‘no’. Others start as the germ of an idea and develop over months or even years. Some are feasible – a new take on a valve (‘tube’, for our US friends) amplifier or a novel use of an Arduino. Many projects sound great but are not always feasible – wouldn’t it be fun to create a ‘flux capacitor’ or ‘sonic screwdriver’?! Yes, of course, but we’re going to have to wait for a few components to be invented before they appear in *PE*.

Some projects look great on paper, but they are ‘just ideas’ and unless we are presented with a functioning circuit it’s too much of a risk to run with an untested project that may have a subtle but fatal design flaw.

A few ideas come our way that look fun and exciting but are inherently dangerous – they may play fast and loose with the mains supply or critical elements of a car. Some are plain illegal. In the UK – and of course elsewhere – we have extremely strict rules about operating transmitters or connecting circuits to the telephone network, which is why you very rarely see such items in *PE*, however much fun they might be.

That said, many of you take the time to write in with ideas and we appreciate that very much.

...at last!

This month, we feature two projects that I have wanted to run for a very long time. The first is a real classic. Nearly 50 years ago Ladybird books published a little volume for children explaining how to build a radio. I built one, *Audio Out’s* Jake Rothman built one, and I expect many of you did too. It was quite a sophisticated circuit and I’ll be as honest as Jake at this point and confess mine didn’t work. This has always bugged me and when Jake suggested we build a *PE* version and offer a few upgrades I agreed immediately. I hope you enjoy this IC-and-PCB-free trip down memory lane. It will be fun!

At the other end of the technology spectrum, this month is when Mike Hibbett’s *PIC18F Development Board* really takes off. The first PCB prototype has been designed, built and (mostly) tested. It looks superb and I hope many of you will build one when it becomes available in the May issue.

Keep well everyone

Matt Pulzer
Publisher

The **Fox** Report

Barry Fox's technology column

Fakes, scams and evasion

Covid has provided a golden opportunity for scammers to con the unwary – and even the wary.

I bought a 2TB USB stick memory which turned out to be a fake. I have since learned that the crooks are using a controller unit which gives a false reading for whatever memory chips it is bonded to. So, using a PC to check capacity is no guide.

Soon afterwards I was stung by a 2TB portable HDD which also failed to store as much data as it should have done. In each case I was able to return the purchase and ask for a full refund. But in each case I lost data.

Price is not necessarily a reliable guide to fakery because the faker may charge a high price to create false confidence.

Fortunately, there are several free software tools now available, such as *H2testw* or *FakeFlashTest*. The downside is that they can take days to fully check a large capacity store. Plus, they may lock up when they hit a capacity problem.

On the face of things, fully formatting a new drive (not quick formatting) should show its true capacity. But it is possible the fakers can – or will soon – fake that too. Once a faking chip is available there is no way of limiting who uses it. This probably explains why there are so many 2TB fakes around.

Arguably the safest guide to genuine quality is the brand name. This can of course also be faked, but phoney products will usually look cheap and phoney.

So, buy memory USBs and HDDs from a source which has a friendly return-and-refund policy that costs only the price of the paper and ink needed to print a pre-paid label.

Answer or ignore?

The scammers are also having a field day with scam phone calls, texts and emails. Phone calls are easy and fun to prolong if you have some time to spare. Just give no personal details and keep the scammer talking to eat into the time they have to call other, perhaps more gullible targets.

Be wary of replying to scam emails and texts, however much fun it might seem to be, because you are just confirming that your ID address is 'live'.

I was recently shocked to hear absurdly bad advice on scam emails given out by a so-called expert on a morning BBCTV programme. Talking about online scams, he advised that if anyone gets a scam email, then they should 'change their password'. The fact that a scammer knows your email does not of course mean that they have access to your email account. It simply means that they have harvested your email from any one of countless possible sources.

Most people get multiple scam emails every day, so anyone taking the BBC's 'expert' advice would be changing their password several times a day; and changing an email password does not stop scam emails arriving.

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I contacted the BBC who waffled that the 'expert' was 'simply offering one way that a person can protect themselves, but we appreciate you did not agree with this advice.' I have now suggested that the BBC ask its own IT Department to confirm that it is not a matter of opinion but fact that advising people to change their password when they receive a scam email is downright wrong; and it is doubly worrying that an 'expert' advising millions is not willing to admit and correct a mistake.

A great big non-answer

As recently reported (*Fox Report*, February 2021) I asked the chief executive of the Advertising Standards Authority, Guy Parker, for his personal views on the ASA's competence to handle consumer complaints about adverts with technical content; and I promised to report back on any response.

With considerable difficulty I did eventually squeeze a personal response from Guy Parker, which reads: 'I recognise your frustration about our newish complaint handling procedures, but my colleagues, including members of my Senior Management Team with responsibility for our Complaints and Investigations operation, have taken time carefully and thoughtfully to respond to your concerns, including committing to review our procedures in light of your helpful feedback. I've nothing to add to that.

'I disagree that the ASA is ill-equipped to judge ad claims for consumer technology products and services. On the contrary, we have a great deal of experience judging such claims.

'While it's obvious that our responses have not satisfied you, there's not much we can do about that and I see nothing to be gained from continuing to correspond. I therefore consider the matter closed and I won't be replying if you choose to write to me again.'

Check for yourself

PE readers can look for themselves at recent ASA rulings, and form their own opinions on whether the number that relate to adverts with a technical slant reasonably reflects the plethora of adverts for tech-based products and services that we now see in the media; see: **http://bit.ly/pe-mar21-asa1**

Readers can also search online for any technical credentials among the ASA's management here: **http://bit.ly/pe-mar21-asa2**

In the meantime, I have filed another tech-related complaint, regarding commercial promotion of consumer tech products by a consumer tech TV personality. So, I can report firsthand that, thus far, there is no sign of the procedural changes needed to keep consumers informed on the progress – or silent dismissal – of their complaints.

This is two full months after the ASA said it would 'look to implement something' based on my 'very helpful suggestion'.

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Marconi 2022E	Synthesised AM/FM Signal Generator 10kHz – 1.01GHz	£325
Marconi 2024	Synthesised Signal Generator 9kHz – 2.4GHz	£800
Marconi 2030	Synthesised Signal Generator 10kHz – 1.35GHz	£750
Marconi 2023A	Signal Generator 9kHz – 1.2GHz	£700

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Tasakago TM035-2	PSU 0-35V 0-2A 2 Meters	£30
Thurlby PL320QMD	PSU 0-30V 0-2A Twice	£160 – £200
Thurlby TG210	Function Generator 0.002-2MHz TTL etc Kenwood Badged	£65

HP/Agilent HP 34401A Digital
Multimeter 6½ Digit £325 – £375

HP33120A	Function Generator 100 microHz – 15MHz	£350
HP53131A	Universal Counter 3GHz Boxed unused	£600
HP53131A	Universal Counter 225MHz	£350
Audio Precision	SYS2712 Audio Analyser – in original box	POA
Datron 4708	Autocal Multifunction Standard	POA
Druck DPI 515	Pressure Calibrator/Controller	£400
Datron 1081	Autocal Standards Multimeter	POA
ENI 325LA	RF Power Amplifier 250kHz – 150MHz 25W 50dB	POA
Keithley 228	Voltage/Current Source	POA
Time 9818	DC Current & Voltage Calibrator	POA

Marconi 2955B Radio
Communications Test Set – £800

No blame, no shame?

Techno Talk

Mark Nelson

Some folk have fabulous luck: every one of their electronic projects works perfectly, every time. The rest of us can feel proud if we are successful most of the time. But what if you really are an expert electronicist and still find yourself completely stuck. What on earth is the cause? Maybe it's not of this earth at all. Confused? Just read on...

Picture this scene. You are building a *Practical Electronics* project, using fresh components bought from reliable suppliers and inserted correctly in the PCB, your soldering is impeccable and after all this effort, the gizmo then refuses point blank to work. You check and re-check your workmanship, then you use a magnifying lamp to seek out minute solder bridges and splashes – all to no avail. You definitely haven't botched anything, so why won't it function properly?

Consult the experts

Have courage – you may be entirely blameless! Even experts can suffer this syndrome. The late Gerry Wells, former curator of the Vintage Wireless Museum in London often encountered problems of this kind. He put them down to what he called 'dirty electricity', and as he always had plenty of repair jobs on hand, he just set aside refusenik projects and got on with something else. But that won't solve the problem of your present project.

Maybe you should look further afield for inspiration. Sherlock Holmes had the right idea, saying: 'When you have eliminated the impossible, whatever remains, however improbable, must be the truth.' 'Fairy nuff', as they say, where do wo go next? Remember when I asked earlier, what on earth is the cause? Maybe the cause is not on earth at all.

Cosmic chaos

A serious contender for causing electronics to malfunction is the effect of cosmic rays from space. These little devils are so devious that they are not really rays at all. Instead, they are high-energy particles that move through space at close to the speed of light, made up of nuclei of elements like hydrogen and helium, along with other subatomic particles such as neutrons, electrons and neutrinos. They originate in stars and the supernova effects produced at the close of life of truly massive stars. Although most cosmic rays and their effects are absorbed by the atmosphere, eight cosmic ray showers reach each square metre of the Earth's surface each second.

They can carry positive or negative charges and although human life at ground level is not affected significantly (space travellers are at greater risk), cosmic rays certainly represent a real risk to electronic devices made of silicon. The most prevalent effect is from bit-flips in memory chips (known as 'soft errors'). It is stated that if you have 1Gb of memory per chip and 1,000 chips, then you can expect 0.4 flips every hour. There is also a real but rare effect known as single event latch-up (SEL), which can cause a transistor to conduct continually until the power is removed.

Vulnerability defined

Earlier investigations into the effect of cosmic rays implicated them in a number of mishaps, such as when the accelerators of Toyota cars throttles became stuck in the open position. This defect, which was said to be possibly the result of cosmic rays, led to the recall of a substantial number of vehicles in 2009 and 2010. Wikipedia also cites data corruption in a flight control system that in 2008 caused an Airbus A330 airliner twice to plunge hundreds of feet, giving rise to injuries to multiple passengers and crew members. Although cosmic rays were investigated initially as a possible cause, this was later ruled out as very unlikely.

Since then, our understanding of the effect of cosmic rays has improved considerably and responsible manufacturers design safety into products that are potentially vulnerable. Statistics play an important role here, as the Silicon Valley PCB manufacturer Royal Circuit Solutions explains on its website at: **http://bit.ly/pe-mar21-cosmic**

Since it is impossible to know exactly when or where a cosmic ray impact will occur, engineers must rely on statistics to determine the probability of impact. Manufacturers provide cosmic-ray data separate from terrestrial radiation sources, quantified in terms of Failure-in-Time, or FIT units. One FIT unit is equal to one failure in one-billion device hours.

That sounds quite impressive until you do the maths. If, for example, a circuit that you designed was installed on 500,000 products and had a single transistor with a 14 FIT rating, you could anticipate a failure every six days. This might be acceptable for a fan on an industrial air-sensor unit. But it would be a wholly unacceptable risk for a device that controls, say, the accelerator on a car.

Please understand that all of the foregoing applies only to electronic devices that are deployed at ground level. In satellites and spacecraft the case is altered entirely, with electronic circuitry requiring special radiation-hardening protection or sophisticated error checking.

Back in the real world

It must be made clear that the likelihood of cosmic rays affecting a hobby electronics project is pretty minimal for now. That said, the situation could increase in times to come. As electronic devices continue to shrink physically and operate at lower voltages, active devices will include more bits per square millimetre, with less electrical charge required to define a bit as being in the 1 or 0 state. On one hand, as electronic packages shrink, the chances of a direct impact by a charge particle decrease. On the other, as operating voltages decrease, the degree of threshold between logic-high and logic-low voltages is reduced, meaning the likelihood of a failure caused by a cosmic ray will increase.

Lessons learnt

So, what have we learnt? At least two things, I would say. First, the effect of cosmic rays is real but only transient, so they are unlikely to have kyboshed circuits that refuse to work. Apologies for raising your hopes; random charged particles from space are not a viable get-out-of-jail card! Second, you probably now know more about cosmic rays than you did five minutes ago. Now start looking for dry joints...

Exclusive offer

Win a Microchip PIC24F LCD and USB Curiosity Development Board

Practical Electronics is offering its readers the chance to win a PIC24F LCD and USB Curiosity Development Board (DM240018) – and even if you don't win, receive a 20%-off voucher, plus free shipping for one of these products.

The PIC24F USB and LCD Curiosity Development Board is a cost-effective, fully integrated development platform that facilitates you to explore segmented LCD interfacing and various features of the low power PIC24F MCUs with a USB and an integrated LCD controller. Designed from the ground-up to take full advantage of Microchip's MPLAB X IDE and MPLAB Code Configurator (MCC), the board includes an integrated programmer/debugger and requires no additional hardware, simplifying your prototyping.

The PIC24F USB and LCD Curiosity Board is the perfect platform to harness the power of a PIC24FJ512GU410 low-power microcontroller with a USB and an LCD controller. Its layout and external connections offer unparalleled access to the Core Independent Peripherals (CIPs). The on-chip CIPs enable you to integrate various system functions onto a single MCU, simplifying the design and keeping system power consumption and BOM cost low.

Worth $45.00 (approx £33.50) each

With the new LCD core independent animation feature, you can visualise display animations come to life, even when the MCU is in a power-saving mode. The board also facilitates you to explore the VBAT function with a secondary coin-cell battery.

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Microchip PIC24F LCD and USB Curiosity Development Board

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https://page.microchip.com/PE-PIC24F.html

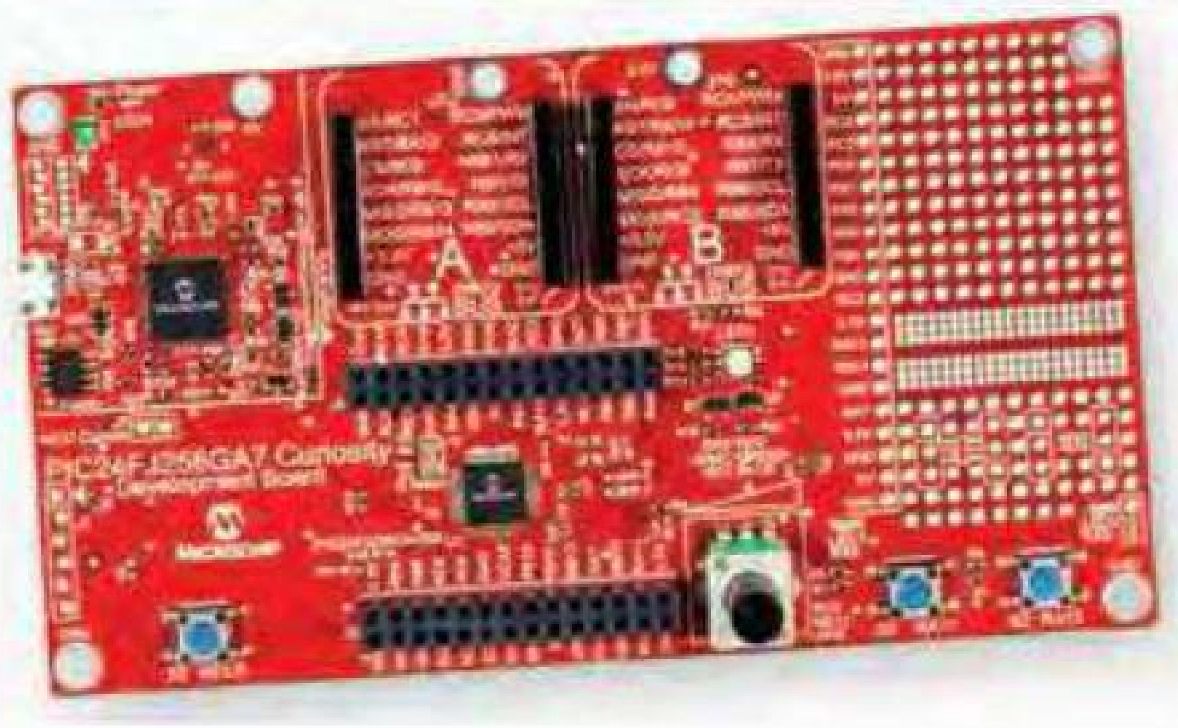
Closing date

The closing date for this offer is 28 February 2021.

November 2020 winner

Tim Wilkinson and Nick Theodorou

They won a Microchip PIC24FJ256GA7 Curiosity Development Board



Net Work

Alan Winstanley

This month, *Net Work* discusses tech for WFH – working from home – especially the all-important webcam for the new normal of video conferencing.

One of the knock-on effects of the Covid-19 crisis has been the migration towards working from home (WFH) rather than commuting to the office. What the commercial office landscape will look like 'post-Covid-19' remains to be seen, but for now many workers are stuck in a strange and surreal world of using a private home (theirs) to conduct their employer's business, blurring the boundary between work and home life. The sale of monitoring and tracking systems has also boomed, which enables creepy bosses to keep tabs on remote workers at home in the same way that call centres control the productivity of their agents. For UK workers and employers facing the need to work from home, a lot of sensible guidance is published on the ACAS website at: **http://bit.ly/pe-mar21-acas**

The WFH phenomenon has also crept into popular culture. In Britain, a TV advert for the Wickes DIY chain focuses on homeworkers busy on video calls, and ponders whether they suffer from so-called 'housebarrassment' – a Wickes portmanteau for showing a tatty kitchen in the background! Naturally, Wickes has the answer in the shape of a trendy new kitchen. It's also become the norm to watch TV news commentators and journalists broadcasting from home, and the phrase 'you're on mute' has landed in our lexicon, aimed at those whose microphone was accidentally turned off.

WFH and 'housebarrassment': a 'dodgy' background hides a tired old kitchen in a video session (Wickes TV ad, Youtube)

The novelty of video conferencing probably wore off long ago and some embattled schoolteachers are understandably struggling to cope with the pressure of Zoom lessons. Some tutors now cite privacy concerns about web-based teaching because their personal property appears in the background during live video sessions, and some schools are forbidding live lessons altogether. Video chat software can often blur the background or swap it for something else, and free stock images of weighty bookshelves (eg, from **unsplash.com**) can easily be superimposed as a backdrop. Pop-up blank screens are also being sold that physically block off the background vista altogether. In Japan and China, the centuries-old concept of *shoji* resulted in those paper-thin sliding partitions made from wooden lattices, which offer privacy as well as diffused lighting, and WFH teleworkers can now buy a stand-up noise-reducing *shoji* screen of their own (see **http://bit.ly/pe-mar21-wfh**) albeit without the paper, or the wooden lattice for that matter.

A nice problem to have

The combination of a global pandemic and working from home has been both a blessing and a curse for Logitech, the US/Swiss-based maker of stylish computer keyboards, mice, speakers and webcams. During 2020, Logitech saw some explosive growth in sales attributed to WFH, though Logitech's CEO Bracken Darrell claimed that the changes in work patterns due to Covid-19 and WFH were already under way: the pandemic simply accelerated those trends. Among other things, Logitech had already predicted the day that video calling would finally overtake audio calls and the workplace would move out beyond the office, he said; doubtless boosted by improvements in Internet speeds. Nevertheless, Logitech and their suppliers have been caught desperately short by the pandemic, as the stampede towards video conferencing and web chats has cleared out stocks of webcams everywhere. Logitech can't make the things quickly enough.

Logitech's C920s is a Full HD 1080p USB webcam with stereo microphones and privacy shutter – if only you can find one.

Totally ilLogitech

About ten years ago a decent quality Logitech webcam with a Carl Zeiss lens might cost £40 (as seen in *Net Work*, Feb. 2012), but today's modern devices are trading at a premium of £150-£250 – that's if you can even get one. A recent PC upgrade from Windows 7 to Windows 10 went smoothly enough for the author, but the aforementioned Logitech HD 9000 proved cludgy and temperamental, its legacy software not marrying very well with Windows 10 or Skype. The camera settings needed coaxing into operation every time, using some very convoluted adjustments. Hence the quest for a new webcam was soon under way, but this would highlight the chaos that reigns in the market for webcams following the rush to work from home.

The author's search for a replacement started with Amazon, who listed a desirable Logitech C920s HD 1080p stereo webcam (the 's' suffix denotes a flip-down privacy shutter), so one was duly

Manfrotto's MCLAMP phone grip and PIXI Mini tripod hold a smartphone firmly in place to help with desktop video sessions. The clamp has two tripod screw threads. Sold separately.

ordered in November 2020 with delivery slated for next February(!). Then, some good news – suddenly it was on the way from Amazon Spain, with delivery due before Christmas. After sourcing, what seemed to be the last Logitech webcam in Europe, the package arrived at a UK airport before being couriered to an Amazon depot just 30 miles away from the writer. Having travelled all the way from Madrid in Spain, it then disappeared without trace and was never seen again; one can only speculate about why a valuable and much sought-after webcam disappeared from Amazon's local depot. Amazon's online webchat was silent except to say that 'it may be lost'. A promised phone call from Amazon never happened, but they added that the webcam could not be replaced either, just to rub it in, and so a refund was forced onto me.

Looking to buy direct from Logitech's website instead, I learned that UK deliveries had been suspended anyway due to impending changes in shipping and customs regulations caused by Brexit, so I drew a blank there as well. UK catalogue store Argos recently listed the same camera on their eBay store as 'Click & Collect only' – but a journey to collect a non-essential item from their store is arguably illegal under lockdown laws.

I don't see an improvement any time soon, though Logitech is now accepting orders for the C920 HD (without privacy shutter) at £89.99 or the C922 streaming webcam (ditto) at £94.99. More details of Logitech webcams are at **http://bit.ly/pe-mar21-cam** if you want to try buying direct. When googling around, beware of bogus screenscraped Logitech software and driver websites with logos similar to Logitech's but which simply want to cash in on Google traffic instead.

As you would expect, Chinese makers have been quick to fill the demand by offering obvious Logitech-lookalikes, mostly sporting strange brand names. Claims about 'no drivers needed' imply that they probably have no native software and are simply dumb, driverless Plug & Play devices with no image controls. Some disappointed reviewers regretted their purchase and recommended waiting for Logitech cameras to return into stock, but others found them good enough for their purposes.

Camera connections

Attention then turned to other gadgets that contain cameras – could I use a smartphone camera as a PC webcam instead? As it turns out, a number of apps are designed for that very purpose. DroidCam by Dev47Apps installs on an Android or iPhone and has a corresponding Windows PC or Linux client program. The program can utilise either the phone's front (selfie) or rear camera and it works via Wi-Fi or USB. After starting DroidCam on your phone, log into the (Windows) client using the suggested IP address. A small window shows the video streaming from your phone. In programs such as Skype, select 'DroidCam Source x' for the camera. Although there is no Mac client, the vendor suggests OBS Studio and DroidCam OBS. If you have a spare phone, DroidCam might also double as a security camera. A paid-for, ad-free upgrade is available. You can download the app via the usual stores, and the PC client can be fetched from: **www.dev47apps.com**

Another practical issue is that of using a smartphone hands-free when it's used as a webcam. All manner of phone holders is sold online, and none really stood out above the others. Some had a pop-out Bluetooth trigger fob for taking photos or selfies by remote control. Also consider phone grips that have a built-in tripod screw thread or suction cups. I like the Manfrotto MCLAMP phone grip, which has a small pop-out angled prop for desktop use, and it will also screw onto a tripod. The matching Manfrotto PIXI Mini Tripod has a smooth push-button ball-joint adjustment and provides a high-quality desktop mount about 150-175mm high. Each part is bought separately and is available from photographic stores or Amazon at around £35 the set.

HeimVision PTZ test

I had to search all the way back to the September 2012 issue of *Net Work* to find my last review of a 'PTZ' camera, a pan/tilt/zoom IP camera that could be used for home security or monitoring via a network connection. Back then, £40 bought an unbranded PTZ camera that worked on Wi-Fi or Ethernet and its spec looked promising – on paper, if nothing else. It had the usual IR night vision LEDs, and its motorised mount could 'patrol' or sweep a preset path, recording any events to disk. I hit numerous problems in failing to record to disk, 'laggy' operation, losing Wi-Fi connections, failure to send email alerts or display images on a mobile phone, the absence of tech support and all the rest of it. It was returned to the vendor.

Technology has come on apace since then, and regular *Net Work* readers might recall my recent test of an outdoor IP camera made by HeimVision, which generally gave good results (*Net Work*, December 2020). I tried both its Wi-Fi and Ethernet feeds over a Devolo-based PLC network with success. HeimVision also produces a PTZ camera for domestic use and a Christmastime price drop to £30 meant it was definitely worth trying. The HeimVision HM202A is a dome-shaped 3MP camera with a motorised base that pans almost a full circle (355°) and tilts up and down up to 95°. It uses either 2.4GHz Wi-Fi or wired Ethernet and has a microphone, speaker, two-way audio of sorts and an empty microSD slot (128GB max). A paid-for cloud service is also available. Once again, I found HeimVision's supplied manual was of good quality, well written and superior to many, with just a few minor variances noted in practice.

Owners must choose wireless or Ethernet at the outset, but installation was simple enough, prompted by voice commands issuing from the camera speaker, and after the camera scanned a QR code on a mobile phone it set itself up on the Wi-Fi network. The Android app was then installed on an Android phone (iOS versions are available).

HD SMART Wi-Fi CAMERA

HeimVision's HM202A is a well-sorted domestic PTZ camera with 355° base, audio, microSD and optional cloud storage. It's very good value at under £35.

XPeng's G3 Smart EV from China is their first model aimed at European markets. Sales have started in Norway.

For the price, performance hasn't been bad, but the Wi-Fi camera has disconnected and needed resetting a couple of times: no good if you're away from home. The app warns that the camera is offline and it also controls the pan and tilt motors; sometimes a time lag needed factoring in, otherwise it overshot the target. Optionally, individual zones can be set up for monitoring and an audible alarm can sound when the camera detects motion.

The microphone proved very sensitive and sound events could also initiate recording. Alerts can be pushed to a smartphone but the 'nagging' can become intrusive after a while. Over the home network, playback in the app of video saved to the microSD card was very good and could not really be faulted. Live footage could be viewed and heard in a web browser as well, and shared privately with up to 10 'family users', though they have no control of lens movement. (Up to four HeimVision cameras can be watched in multi-view mode.) On the home LAN, performance was reasonable, but I cannot vouch for results when viewed over the web halfway round the world.

The camera also records clips if it recognises 'humanoid outlines' but the 'Intelligent tracking' option was of limited use. A plastic mounting bracket is adequate for interior wall or ceiling fitting, and images can be flipped 180° when ceiling-mounted. So far, the HeimVision HM202A is proving a reasonably good PTZ package with none of the rough edges that unbranded Asian devices often have, but don't expect the earth at these budget prices. It would be adequate for monitoring kids, pets or elderly people at home, for example. It's available from Amazon (code B0861535NG) – keep an eye out for discount vouchers.

Giving up the ghost

Deliveries by courier (webcams excepted) have become the norm for many households during lockdown, and a nearby resident said that, after Christmas, he had never seen so many empty Amazon cartons at the local recycling centre (rubbish dump)! It seems anything can be shipped by courier: one of the strangest deliveries I ever signed for was a neighbour's live tarantula, which arrived in a large carton with airholes punched in the side. Perched on the kitchen table, I kept a beady eye on the box waiting for a hairy leg to pop out and greet me.

In January's *Techno Talk* column, Mark Nelson recounted how 'squirrel cage' filament bulbs caused radio blackouts for pilots flying in or out of Glasgow airport. It turns out these vintage-style bulbs can generate RF interference like crazy. It reminded me of a friend who also lives in Scotland, and one day she went outside to sign for a delivery. She described how the courier struggled to open the van doors because the central locking had stopped working. 'Oh, it's because we have a ghost!' my friend exclaimed. She went back indoors 'to have a wee word with the ghost' and returned moments later. The central locking sprang back into life and an ashen-faced courier fled the property, vowing never to return again. The 'ghost' was in fact the under-cabinet lights in the kitchen – switching them off enabled the driver's key fob to work again. Works every time.

Finally...

A trip to a local Tesco supermarket, not visited for many months due to lockdowns, revealed a surprise in the car park: new electric vehicle (EV) charging points had appeared and one EV was already hooked up while its owner went inside to do some shopping. Installed in co-operation with Volkswagen and Pod Point, Tesco aims to install more than 2,400 charging stations in 600 stores nationally, they say. Expect to see some 'Voltswagen' [sic] charging stations in a Tesco car park near you any time soon. In the US, Volkswagen is testing how well EV charging stations operate in extreme conditions, having recently built a test site with 25 bays in the middle of the Arizona desert, says *Autoevolution*.

The dizzying scramble for electric vehicles continues. BMW has opened its order book for its new electric SUV called the iX. Laden with luxury and dripping with tech, the BMW iX has a 100kWh battery and a range of about 375 miles. BMW is currently taking pre-orders online, and a new one is estimated to set you back an estimated £80,000, the *What Car* web site says. Chinese brand Xpeng Motors (or more fully, Guangzhou Xiaopeng Motors Technology Company Ltd.), currently unknown in the UK, has launched what it describes as a 'super-long range smart SUV' called the G3, selling 100 of them in Norway with ambitions to follow up with a very stylish gull-wing P7 saloon across Europe. For a sign of things to come, see **http://bit.ly/pe-mar21-p7**

China's Great Wall Motor (GWM) previously had a short-lived foray into the UK market, selling a basic but sturdy pickup truck. Farmers liked them but it seems spares were difficult to obtain and eventually trucks got laid up in farmer's sheds. The brand withdrew due to EU engine compliance laws, but in China GWM now has a joint venture with none other than BMW, and aims to produce a new upmarket brand of both internal combustion and EV autos which could see GWM on sale once again. Add in the lower-cost electric cars sold by a reborn MG Motors (see *Net Work*, December 2020), and plenty of innovations in the EV segment are heading our way.

Elon Musk's Space Exploration Technologies Corp (SpaceX) has received UK type approval for their broadband terminals designed for the expanding Starlink low-earth orbit satellite network. A new company (Starlink Internet Services UK Limited) was formed in August 2020 to handle the sale of SpaceX satellite-based broadband to UK customers, and the hardware is expected to cost £439 with services costing £89 per month, according to tech site *The Register*. It will be interesting to see whether some English homes need planning permission for SpaceX dishes; in the early 2000s when two-way satellite broadband was tested in Britain by Tiscali, the writer's local council demanded planning permission if your property already carried a satellite TV dish.

Meanwhile OneWeb, rescued from bankruptcy by the UK Government and India's Bharti Global, has successfully launched 36 more satellite launches into low-earth orbit using a Soyuz vehicle, bringing the count to 110 satellites as a precursor to providing commercial services later this year. If you live in a broadband 'not spot' then satellite Internet services may be the solution.

Join me next month for more *Net Work!*

The author can be reached at:
alan@epemag.net

Radio Controlled House Lights

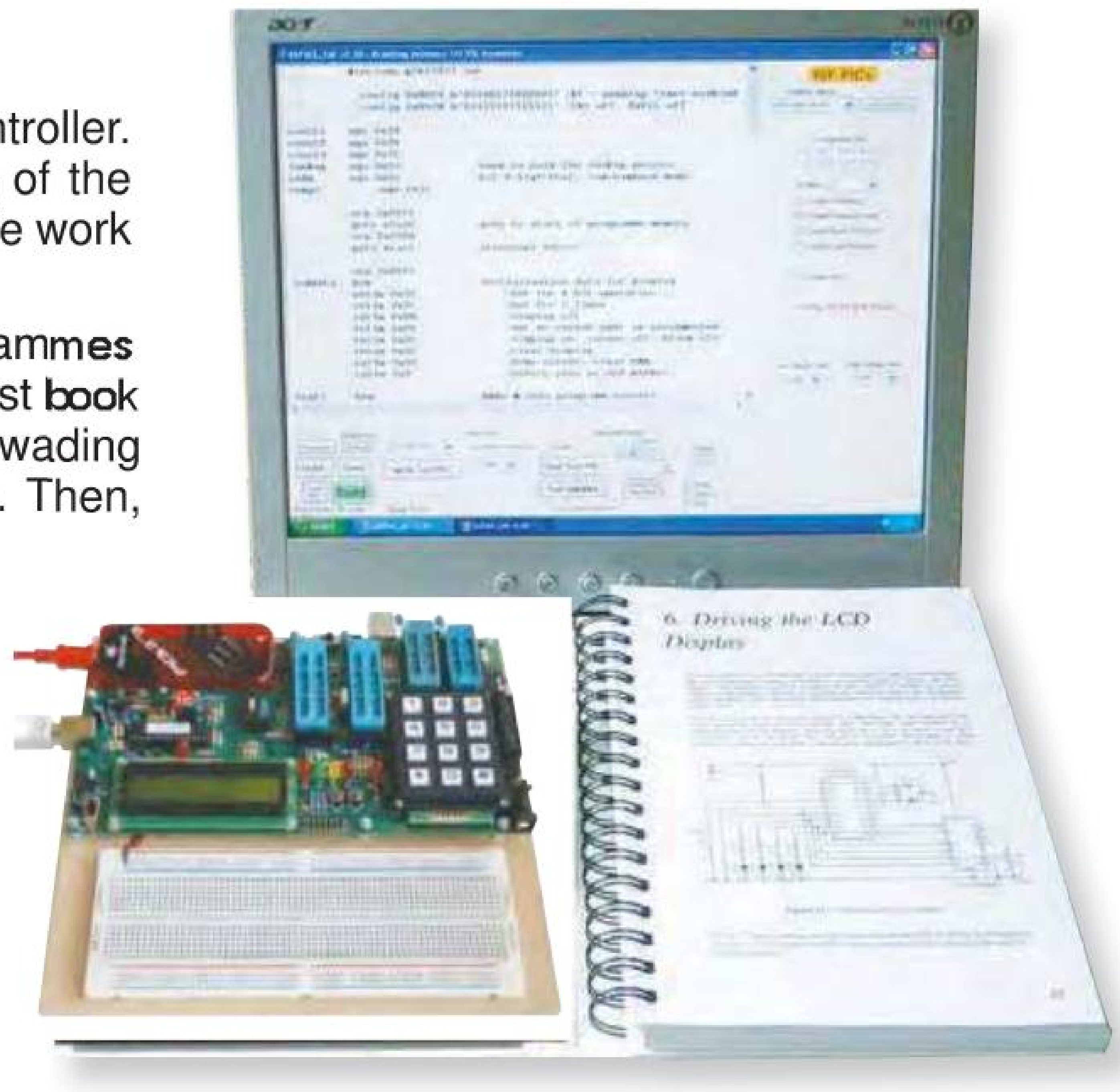
by Peter Brunning

18:00:24
Light Awake 0000

In this short course you will learn how to programme a PIC in assembler to transmit and receive Radio Frequency data. Our objective is to create a system using three radio-controlled house lights so that the lights are switched in synchronism to give the appearance of movement around your house when you are out for the evening or on holiday. We learn about the need to use a unique header so our data can be recognised and create the simplest system to switch a house light on and off. We expand the system using the PIC to count real time. We split the day into three time zones then set up switching patterns for each zone: LightAwake, DarkAwake and Asleep.

The hardware needed for this course is shown in the picture. There is also a 100-page training manual and assembler programme and assembler text on CD. This course can either be bought as a kit with four PCBs and components, or fully built and tested. If you choose to build the PCB you will need to have experience of building circuits which connect to live mains. See website for full details.

The Brunning Software P955H PIC Training Course



We start by learning to use a relatively simple 8-bit PIC microcontroller. We make our connections directly to the input and output pins of the chip and have full control over the internal facilities of the chip. We work at the grassroots level.

The first book teaches absolute beginners to write PIC programmes using assembler, which is the natural language of the PIC. The first book starts by assuming you know nothing about PICs, but instead of wading into the theory we jump straight in with four easy experiments. Then, having gained some experience, we study the basic principles of PIC programming, learn about the 8-bit timer, how to drive the alphanumeric liquid crystal display, create a real-time clock, and experiment with the watchdog timer, sleep mode, beeps and music. Then there are two projects to work through. In the space of 24 experiments, two project and 56 exercises we work through from absolute beginner to experienced engineer level using the latest 8-bit PICs (16F and 18F).

The second book introduces the C programming language for 8-bit PICs in very simple terms. The third book, *Experimenting with Serial Communications*, teaches Visual C# programming for the PC so that we can create PC programmes to control PIC circuits.

In the fourth book, we learn to programme 32-bit MX PICs using fundamental C instructions. Flash the LEDs, study the 16-bit and 32-bit timers, write text to the LCD, and enter numbers using the keypad. This is all quite straightforward as most of the code is the same as already used with the 8-bit PICs. Then life gets more complex as we delve into serial communications with the final task being to create an audio oscilloscope with advanced triggering and adjustable scan rate.

The complete P955H training course is £259, which includes the P955H training circuit, four books (240 × 170mm, 1200 pages total), six PIC microcontrollers, PIC assembler and programme text on CD, two USB-to-PC leads, a pack of components, and carriage to a UK address. (To programme 32-bit PICs you will need to plug in a PICkit 3 or 4. You can buy PICkit 4 from Microchip for £44).

Prices start from £175 for the P955H training circuit with Books 1 and 2 (240 × 170mm, 624 pages total), two PIC microcontrollers, PIC assembler and programme text on CD, USB-to-PC lead, and carriage to UK address. (PICkit 3 or 4 not needed for this option.) You can buy Books 3 and 4, USB PIC, 32-bit PIC and the components kit as required later. See the Brunning website for details: **www.brunningsoftware.co.uk**

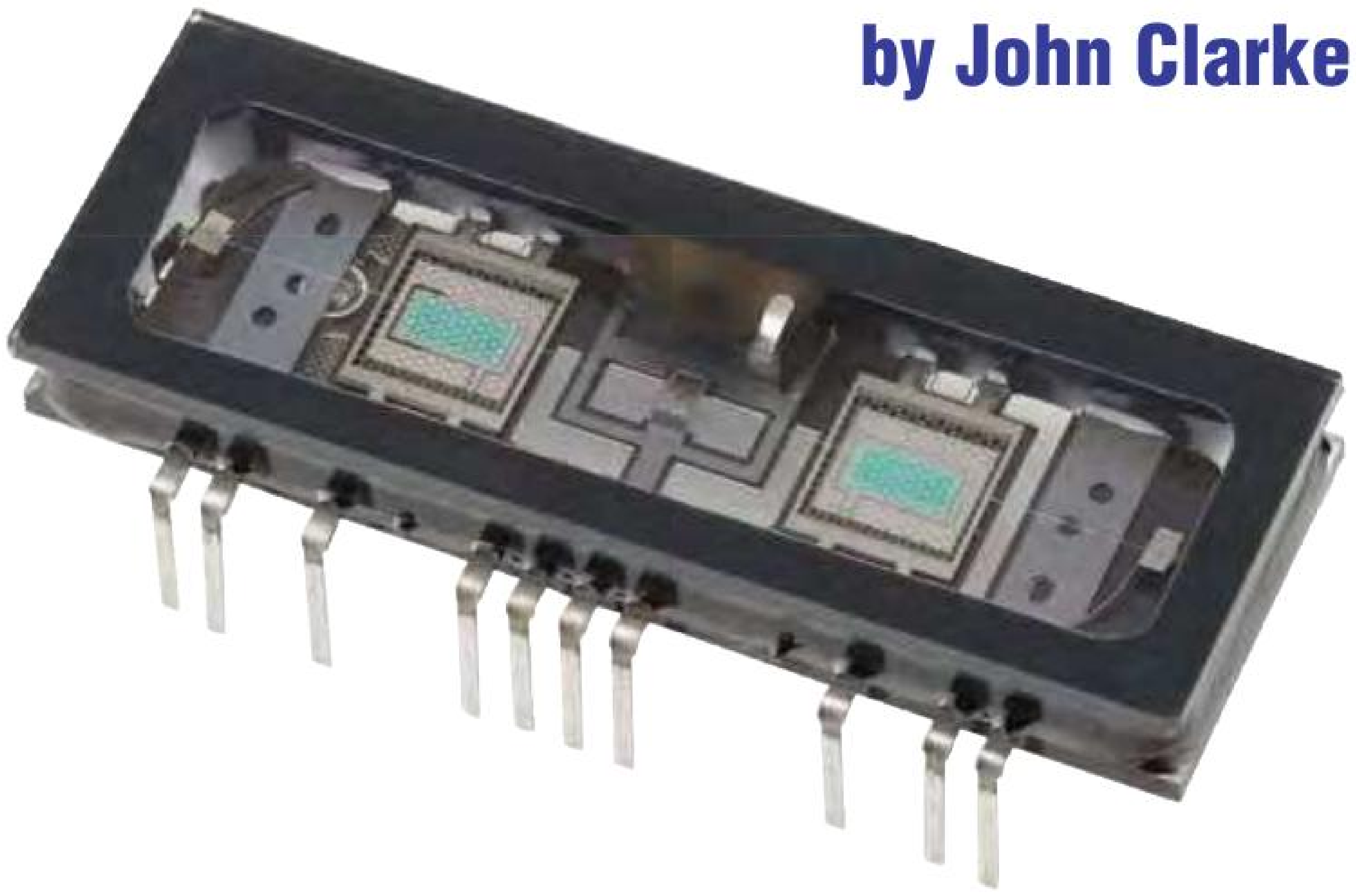
Mail order address:

Brunning Software

138 The Street, Little Clacton, Clacton-on-sea,
Essex, CO16 9LS. Tel 01255 862308

Nutube Guitar Overdrive and Distortion Pedal

by John Clarke



Do you long for that true 'valve sound' in a guitar and distortion pedal? How about this one – it uses a unique low-voltage twin triode valve, so you know it's the real deal!

Electric guitars are almost always played (at least professionally) with some sort of effects in the loop. Acoustic guitars with electric pickup can also take advantage of an effects pedal.

Among the many effects pedals available, overdrive and distortion are probably the most popular. Some produce a harsh distortion (as in 'fuzz boxes'), while others provide a more gentle form of distortion.

Effects boxes commonly use circuitry with semiconductors such as JFETs for providing these effects, and sometimes silicon diodes for distortion.

But the 'Holy Grail' overdrive effect is produced by valves. While some solid-state overdrive pedals attempt to emulate the distortion effect produced by valves when overdriven, there is no substitute for the real thing.

To date, it has been difficult to incorporate valves into a small effects pedal. But that has all changed now that a compact low-voltage 6P1 dual triode is available from music instrument manufacturer Korg.

We introduced it in the January 2021 issue with our *Valve Preamplifier*. This month's project can be used as a distortion pedal, an overdrive pedal or a mixture of both. Two stages of distortion and/or overdrive are included, and the first stage can be used on its own or in conjunction with the second stage that's switched in by the boost pedal.

Overdrive versus distortion

The main difference between overdrive and distortion is in the type of distortion produced. *Overdrive* is when an amplifier is driven with a high signal level, causing the output to be rounded off and eventually, limited or clipped. So at low signal levels, there is no or little distortion. The distortion rises as the signal level increases.

Once the signal becomes limited, the volume remains constant and does not increase significantly as the input signal level increases.

A side effect of excessive overdrive is that it tends to also act as a sustain effect, where the volume level remains constant for some time after the string is struck. The sustain effect continues until the signal from the guitar drops below the level required for limiting.

The type of overdrive distortion depends on how the signal is limited. With valves, the limiting is usually asymmetric, with one polarity of signal excursion more sharply clamped than the other.

A *distortion* effect is different, in that there is a deliberate attempt to distort the signal even at low levels, and the output level is not restricted as much as for overdrive. In other words, there is generally some distortion at all signal levels. We have provided some oscilloscope traces that show the differences between overdrive and distortion (Scope1-Scope8), later in the article.

Our *Guitar Overdrive and Distortion Pedal* can be set up for overdrive or distortion via its control knobs.

Features

- Two distortion stages
- High input impedance suits most pickups
- Gain, output level, distortion and tone controls
- True bypass and boost switches with LED indicators
- Housed in a rugged diecast enclosure
- No high voltages
- Uses a Nutube dual triode with no transformers
- Nutube plate glow is visible
- 30,000-hour Nutube life
- Low power consumption
- Battery or DC plugpack power
- Signal phase preserved from input to output
- Automatic and silent on/off switching
- Power supply reverse-polarity protection

If the distortion controls are set to minimum and the gain increased, the pedal acts as an overdrive, rounding off the higher signal levels. If the controls are adjusted for more distortion, then it acts as a distortion pedal, with the gain level determining whether it is also producing an overdrive effect.

The distortion control in each stage can be set at the mid position for minimum distortion, or closer to either end for more distortion. When wound anti-clockwise, the negative half of the waveform is distorted, but the positive half is not as affected. Conversely, in a more clockwise position, the positive half of the waveform is distorted, but the negative portion of the waveform isn’t as affected.

The *Overdrive and Distortion Pedal* has two stages that provide distortion, with both used when boost is selected. If the first stage is set for positive distortion and the second stage set for negative distortion, both halves of the waveform will be distorted with boost activated. With the boost off, only the distortion provided by the first stage is in effect.

This difference is more noticeable if the signal level applied to the second stage is reduced in level to match that applied to the first stage. This can be achieved by adjusting a trimpot inside the pedal housing.

A tone control is included that provides treble cut. The cut-off frequency is adjustable between about 2kHz and 23kHz. A lower cut-off frequency reduces the distortion harmonics to get the desired sound.

The output levels for when boost is in and out are also adjustable. How you set these depends on the effect you want. The level when boost is switched out is typically set to provide the same output level when bypass is enabled.

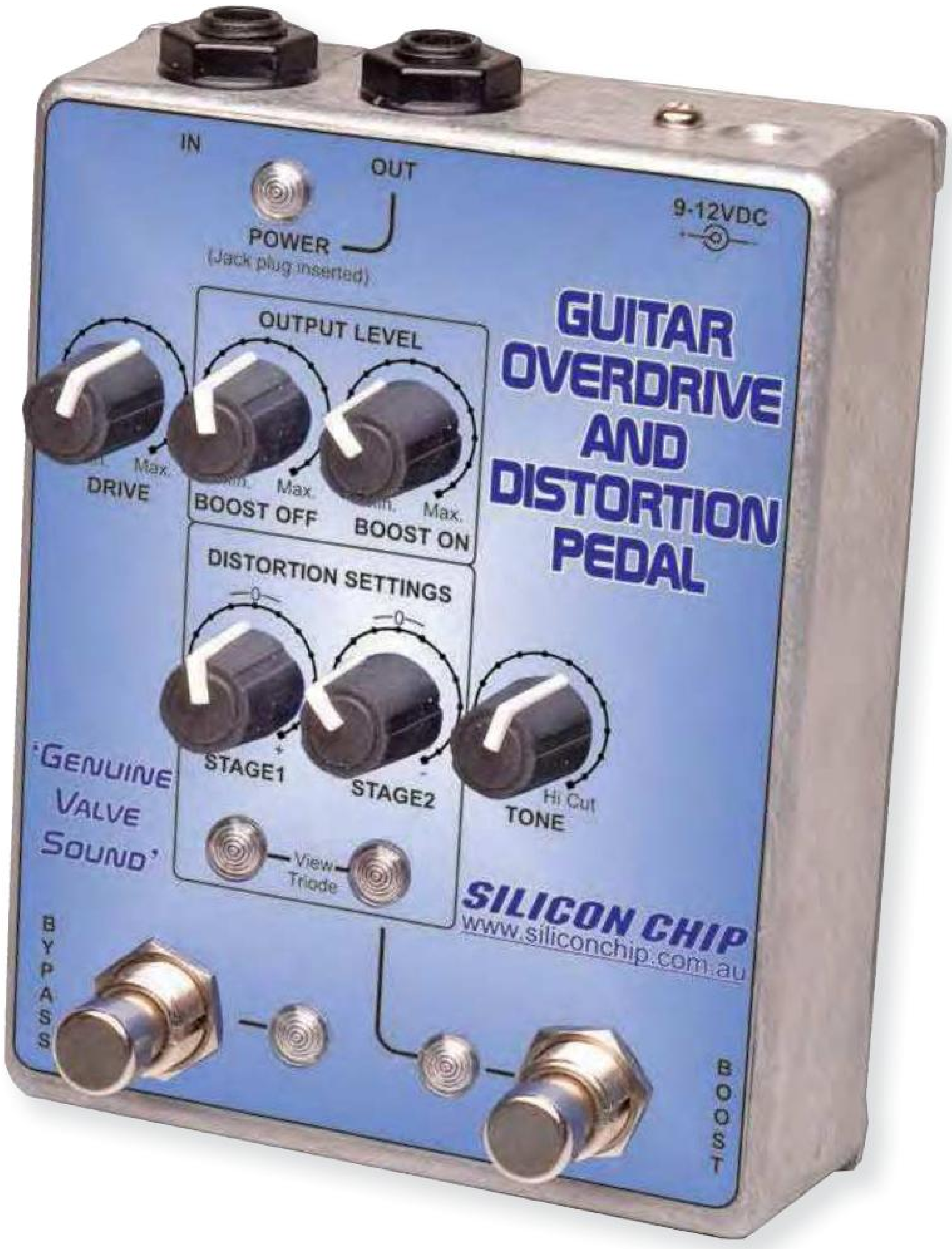
When the pedal is in bypass, the input signal is directly connected to the output. When not in bypass, the signal passes through the distortion and overdrive circuitry.

You could set the output level when boost is selected for a higher level, or at the same level as when boost is off. In general, the boosted output sounds louder anyway, due to the more squared waveform and added harmonics.

Presentation

The *Overdrive and Distortion Pedal* is housed in a rugged diecast aluminium case. It has two foot switches, six rotary controls and three indicator LEDs. Clear bezels are located over the two dual triode plates so that the grid bias setting can be observed (more about this later) and so that everyone can see your magnificent valves glowing.

Two 6.35mm (1/4-inch) jack sockets at the rear provide signal input and output connections, with a DC socket to supply power. The unit can also be powered from an internal 9V battery. Power is automatically switched on when a plug is inserted into the output socket


IN
OUT
POWER
(Jack plug inserted)
9-12VDC
GUITAR OVERDRIVE AND DISTORTION PEDAL
OUTPUT LEVEL
DRIVE
Max.
Min.
BOOST OFF
BOOST ON
DISTORTION SETTINGS
STAGE1
STAGE2
TONE
Hi Cut
'Genuine Valve Sound'
View Triode
SILICON CHIP
www.siliconchip.com.au
BYPASS
BOOST

The *Valve Guitar Overdrive and Distortion Pedal* is housed in a sturdy diecast case, not only for hum minimisation but to ensure heavy-footed ‘axepersons’ don’t do any damage in the heat of the moment. It operates from 9-12V DC (yes, it is a genuine valve) so you can use it with a plugpack supply or even a battery.

Operation

Fig.1 shows a simplified block diagram of the *Overdrive and Distortion Pedal*. The signal from the guitar at CON1 can pass directly to the output at CON2 via bypass switch S2b. When bypassed, the signal passes to the first gain stage. This has a high input impedance buffer stage (IC1a), an attenuator (potentiometer VR1) and an 11-times amplifier (IC1b).

The first distortion stage uses one of the Nutube Triodes (V1b) to provide amplification and distortion. The amount of distortion produced by this stage is adjustable via potentiometer VR2.

The output of V1b is buffered by op amp IC2a. As V1b inverts the signal, the output of IC1a is fed to an inverter

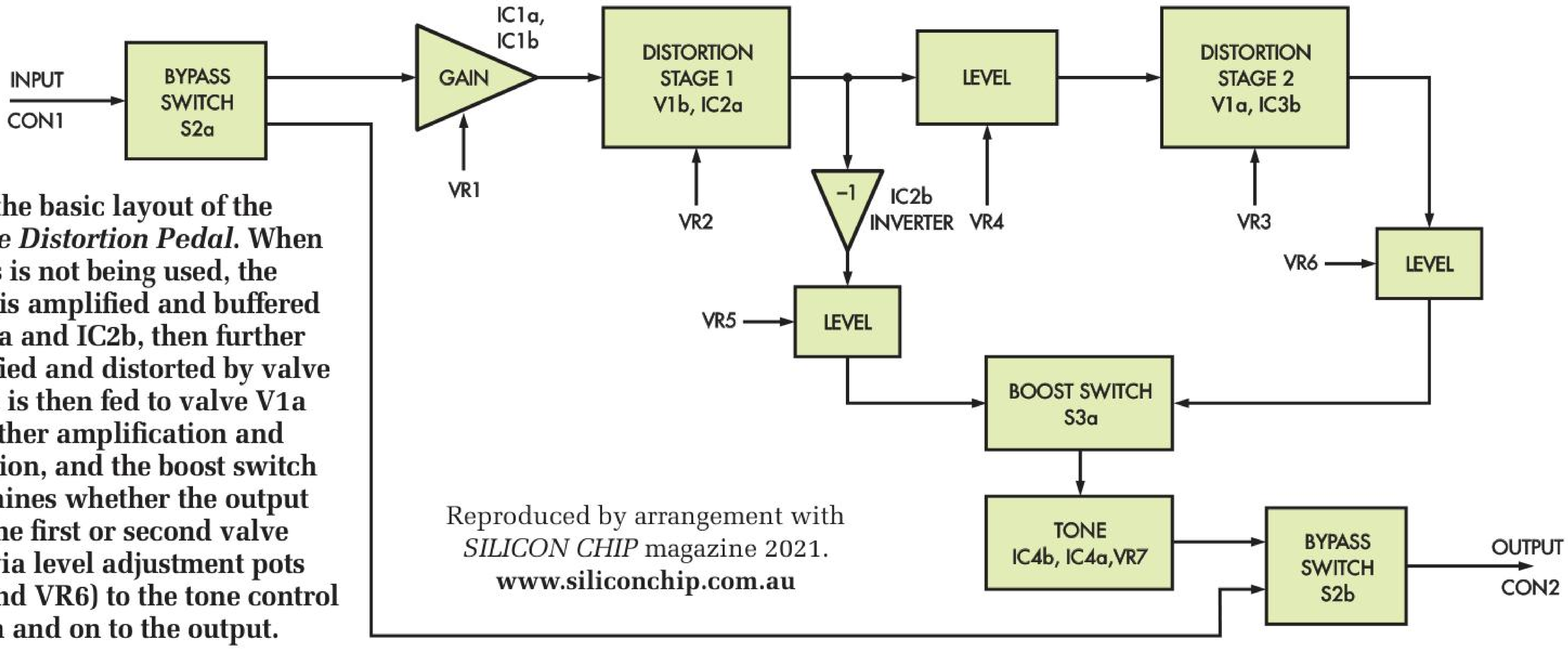

INPUT
CON1
BYPASS SWITCH S2a
IC1a, IC1b
GAIN
VR1
DISTORTION STAGE 1 V1b, IC2a
VR2
–1
IC2b INVERTER
LEVEL
VR4
DISTORTION STAGE 2 V1a, IC3b
VR3
VR6
LEVEL
VR5
LEVEL
BOOST SWITCH S3a
TONE IC4b, IC4a,VR7
BYPASS SWITCH S2b
OUTPUT
CON2

Fig.1: the basic layout of the *Nutube Distortion Pedal.* When bypass is not being used, the signal is amplified and buffered by IC1a and IC2b, then further amplified and distorted by valve V1b. It is then fed to valve V1a for further amplification and distortion, and the boost switch determines whether the output from the first or second valve goes (via level adjustment pots VR5 and VR6) to the tone control section and on to the output.

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Design specifications

- Supply...9-12V DC @ 47mA with bypass and boost LEDs off (+6mA for each LED)
- Gain..32dB maximum with boost off; up to 43dB with boost on
- Frequency response ....–0.6dB at 20Hz. Upper frequency response is dependent on the tone setting
- Tone control...20dB/dec high-cut filter, –3db point varies from 2.12-23.4kHz with tone control
- Maximum input and output swing..................2.3V RMS for 9V supply; 3.3V RMS for 12V supply
- Minimum signal level for overdrive limiting....55mV without boost, 15.5mV with boost
- Signal to noise ratio..82dB with respect to 55mV in and 55mV out.

(IC2b), restoring its original polarity. The output level from the inverter is adjusted by VR5, and the signal then goes to one side of the boost switch, S3a.

The output from before inverter IC2b is also applied to a level-adjustment trimpot (VR4) and then fed to the second distortion stage. This allows the second distortion and overdrive block to have the same input signal level as the first block. In that case, VR4 is adjusted to reduce the signal level from the first stage by about 15dB.

Alternatively, VR4 can be set to provide the full signal level to the second distortion block, to maximise limiting and overdrive.

The second distortion block circuitry is the same as the first, only it uses triode V1a and buffer IC3b. Potentiometer VR3 sets the distortion level while the output level is adjusted with potentiometer VR6. The resulting signal is applied to the other side of the boost switch, S3b.

So the boost can select between the signals from the first or second distortion stages. The selected signal goes to the tone control with adjustable high-frequency cut, as set by potentiometer VR7.

The output from the tone control then goes to one side of the bypass switch, S2b. The bypass switch selects between this signal or the input signal at CON1 (when in bypass).

The Nutube twin triode

One of the things that makes the Nutube so special is that it can run at a very low voltage. Traditional valves require a high anode voltage (above 100V). The Nutube 6P1 was developed by Korg and Noritake Itron of Japan. While it is

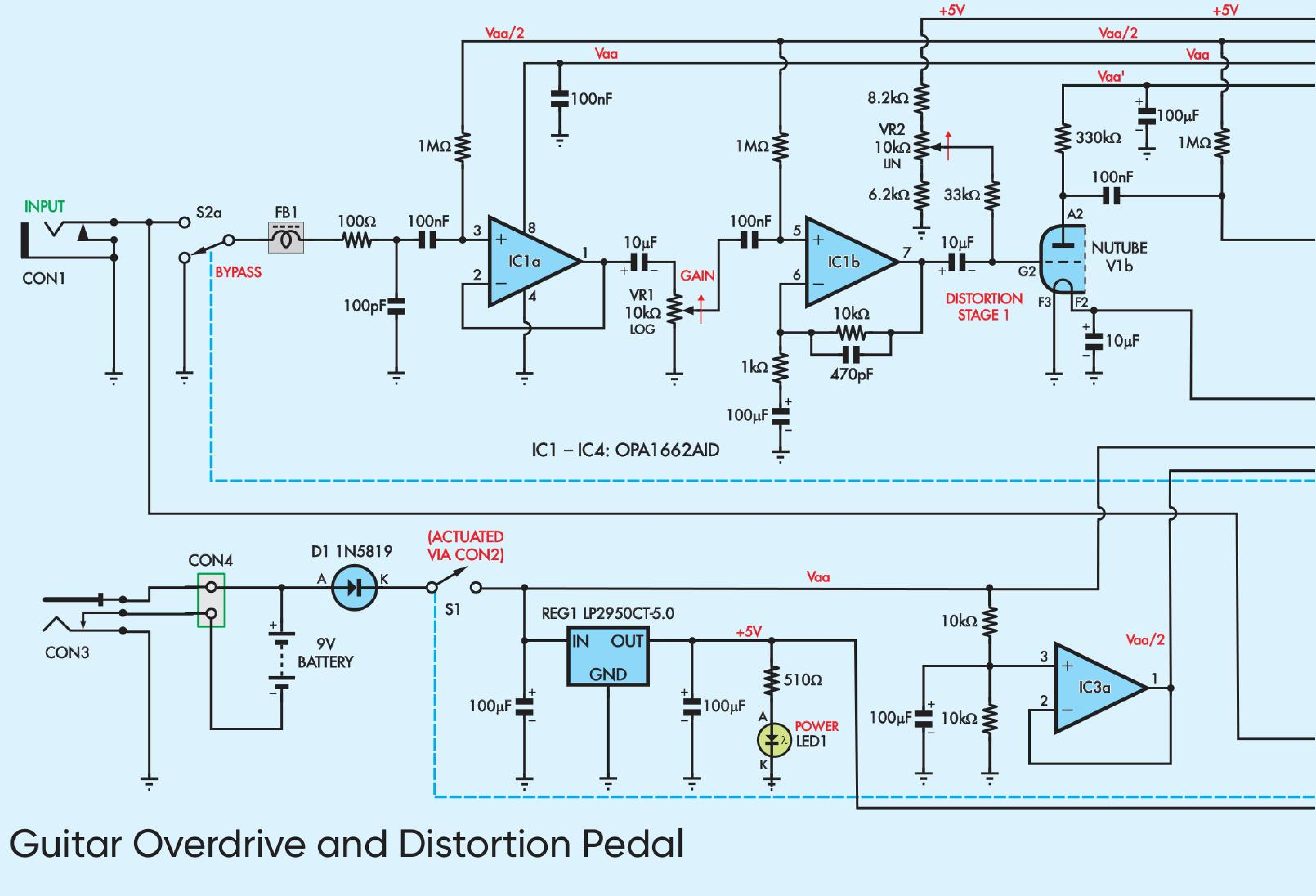

+5V
+5V
Vaa/2
Vaa/2
Vaa
Vaa
Vaa'
100nF
1MΩ
1MΩ
8.2kΩ
VR2
10kΩ
LIN
6.2kΩ
33kΩ
330kΩ
100μF
1MΩ
100nF
A2
INPUT
CON1
S2a
BYPASS
FB1
100Ω
100nF
100pF
IC1a
3
2
8
4
1
10μF
GAIN
VR1
10kΩ
LOG
100nF
IC1b
5
6
7
10kΩ
470pF
1kΩ
100μF
10μF
DISTORTION STAGE 1
G2
F3
F2
NUTUBE
V1b
10μF
IC1 – IC4: OPA1662AID
CON4
D1 1N5819
A
K
(ACTUATED VIA CON2)
S1
CON3
9V BATTERY
REG1 LP2950CT-5.0
IN
OUT
GND
100μF
100μF
+5V
510Ω
POWER
LED1
A
K
Vaa
10kΩ
10kΩ
100μF
Vaa/2
IC3a
3
2
1
Guitar Overdrive and Distortion Pedal

Fig.2: the circuit diagram of the *Valve Guitar Overdrive and Distortion Pedal*. Potentiometers VR2 and VR3 set the grid bias voltages for valves V1b and V1a, and in doing so, determine the amount and nature of distortion that they introduce. The signal from the output of V1b to the input of V1a (via buffer IC2a and attenuator VR4) also goes to pin 6 of IC2b, which acts as an inverter, so that the non-boosted and boosted signals on either side of switch S3a are in-phase.

a directly-heated triode with a filament, grid and plate, it is made in a way that more resembles a vacuum fluorescent display (VFD) than a traditional valve (or tube).

The Nutube has rectangular glass encapsulation, and each triode comprises a single-pixel VFD. Its internal construction has the heater filament as a fine-gauge wire running across the front, with the metal mesh grid located below that. Behind the grid is the plate (or anode), which is phosphor-coated and glows when the filament is heated.

The filament wire is held taut, so it can vibrate (like a guitar string). This vibration is not necessarily a wanted feature as it can be the source of microphonics, where an external sound can couple to the filament and alter (or modulate) the audio signal being amplified. As a result, this vibration is heard in the sound. Careful construction methods can minimise microphonics. This includes protecting the Nutube from surrounding air vibrations, by using flexible wiring, and a vibration-damped mounting method.

In operation, the Nutube draws minimal current, with each filament requiring just 17mA. The grid and plate currents total around 38μA. The Nutube is best operated with a plate voltage of 5-30V. The load-line curves show that within this voltage range, the grid voltage needs to be above the cathode filament voltage.

This is different from the traditional triode, where plate voltages are much higher, and the grid voltage is usually negative with respect to the cathode. Nutube distortion can be adjusted by varying its grid bias voltage.

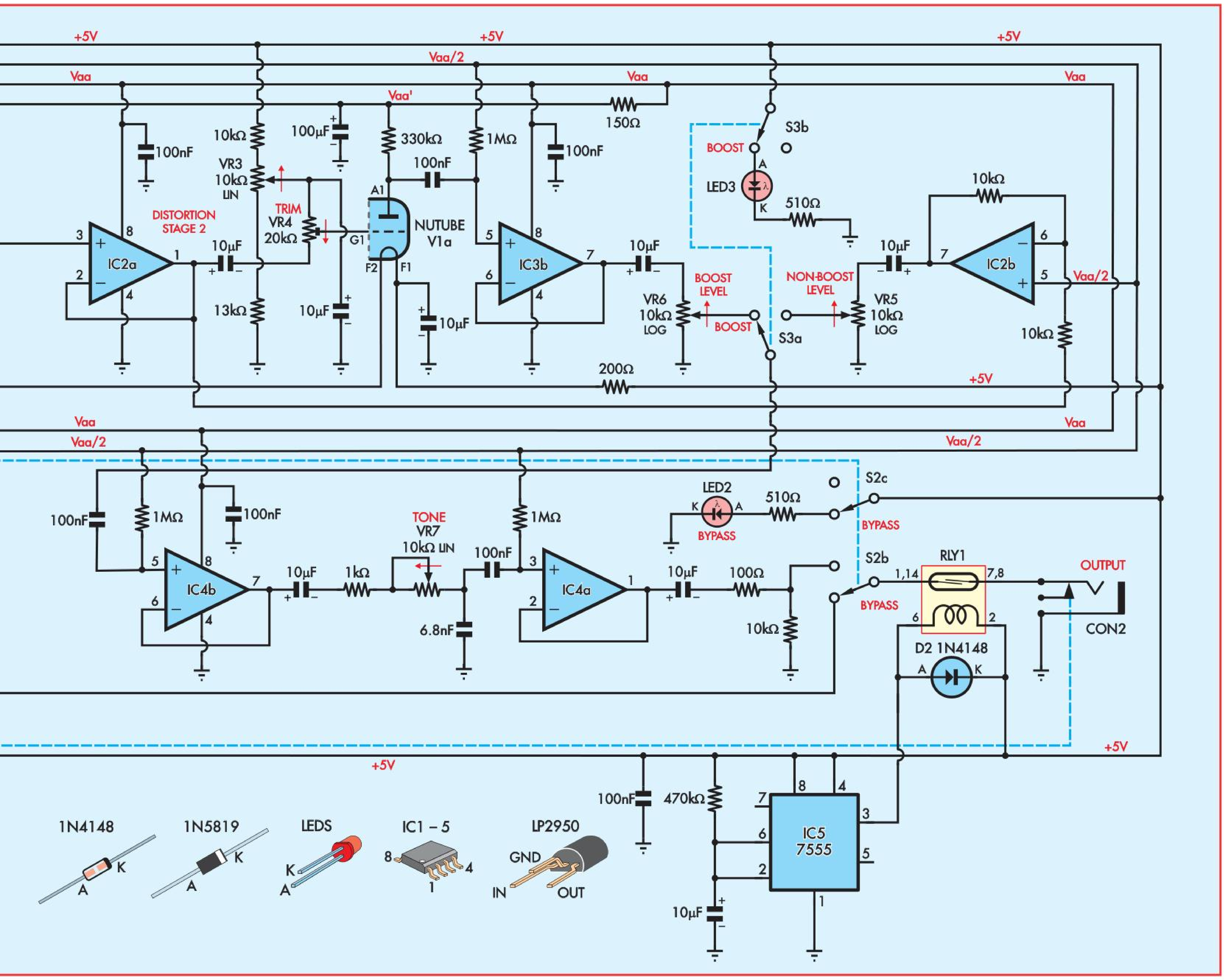
Circuit details

The circuit is shown in Fig.2. You can see the two halves of the Nutube near the upper middle, with both connected as common-cathode amplifiers; the cathode filaments are connected to ground at pin F3. Signals are applied to the grids (G2 and G1), and the resulting amplified signal appears at the anodes (or plates), A2 and A1. The anodes have resistive loads to the positive supply, Vaa.

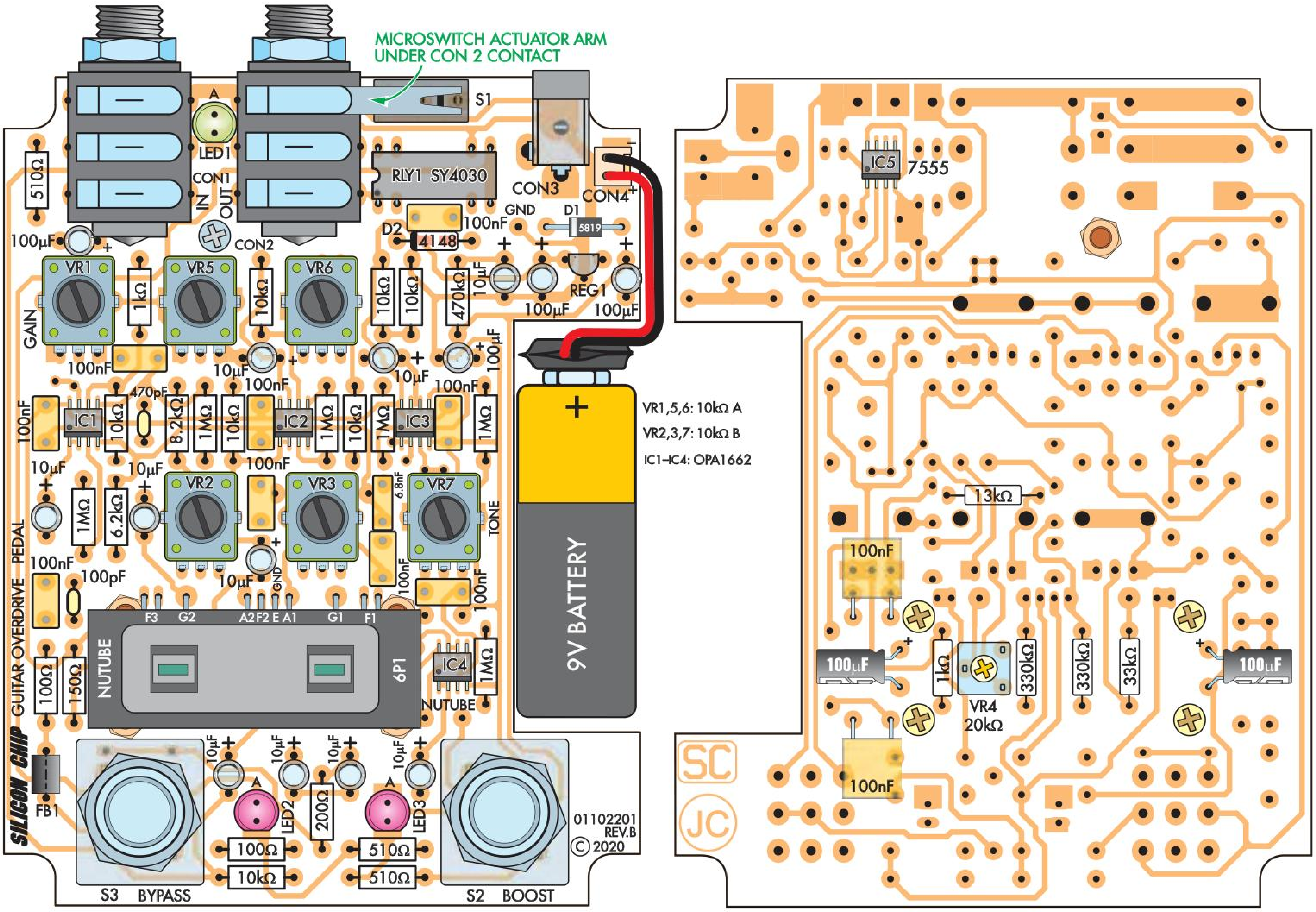
The Nutube triodes have a relatively low grid input impedance and high output impedances at the anodes. Therefore, buffers are used; one to provide a low-impedance drive for the grid of each triode, and others to keep the anode load impedances high. These op amps (OPA1662A) have very low noise and distortion, of around 0.00006% at 1kHz, 3V RMS, and unity gain. So the op amps do not affect the sound of the signal in any way. Any noise or distortion they might introduce is dominated by that from the triodes.

The signal path is as follows. When the bypass switch (S2a) is in the non-bypass position, the signal passes through ferrite bead FB1 and a 100Ω stopper resistor. These, in conjunction with the 100pF capacitor, stop RF signals from entering the circuit, which may result in unwanted radio frequency detection and reception. The 100pF capacitor also provides loading for piezo guitar string pickups.

The signal is AC-coupled to pin 3 of op amp IC1a and biased to half supply (Vaa/2) via a 1MΩ resistor. The *Pedal's* input impedance is therefore high at 1MΩ , making it suitable for a piezo guitar pickup.



+5V
Vaa
Vaa/2
Vaa'
10kΩ
100μF
330kΩ
1MΩ
100nF
150Ω
S3b
BOOST
LED3
A
K
510Ω
10kΩ
VR3
10kΩ
LIN
TRIM
VR4
20kΩ
DISTORTION
STAGE 2
A1
G1
NUTUBE
V1a
F2
F1
IC2a
IC3b
IC2b
10μF
13kΩ
BOOST
LEVEL
VR6
10kΩ
LOG
NON-BOOST
LEVEL
VR5
10kΩ
LOG
S3a
200Ω
LED2
BYPASS
S2c
TONE
VR7
10kΩ LIN
1kΩ
6.8nF
IC4b
IC4a
100Ω
S2b
RLY1
1,14
7,8
6
2
D2 1N4148
OUTPUT
CON2
470kΩ
IC5
7555
1N4148
1N5819
LEDS
IC1 – 5
LP2950
GND
IN
OUT


MICROSWITCH ACTUATOR ARM UNDER CON 2 CONTACT
S1
LED1
CON1
IN
OUT
RLY1 SY4030
CON3
CON4
GND
D1
5819
D2
4148
CON2
REG1
510Ω
100µF
100nF
VR1
VR5
VR6
1kΩ
10kΩ
470kΩ
10µF
GAIN
470pF
8.2kΩ
1MΩ
IC1
IC2
IC3
VR2
VR3
VR7
6.2kΩ
6.8nF
TONE
100pF
GND
F3 G2 A2 F2 E A1 G1 F1
NUTUBE
6P1
IC4
100Ω
150Ω
GUITAR OVERDRIVE PEDAL
SILICON CHIP
FB1
LED2
LED3
200Ω
510Ω
S3 BYPASS
S2 BOOST
01102201 REV.B © 2020
9V BATTERY
VR1,5,6: 10kΩ A
VR2,3,7: 10kΩ B
IC1–IC4: OPA1662
IC5
7555
13kΩ
VR4 20kΩ
330kΩ
33kΩ
SC
JC

(TOP OF PCB)

(UNDERSIDE OF PCB)

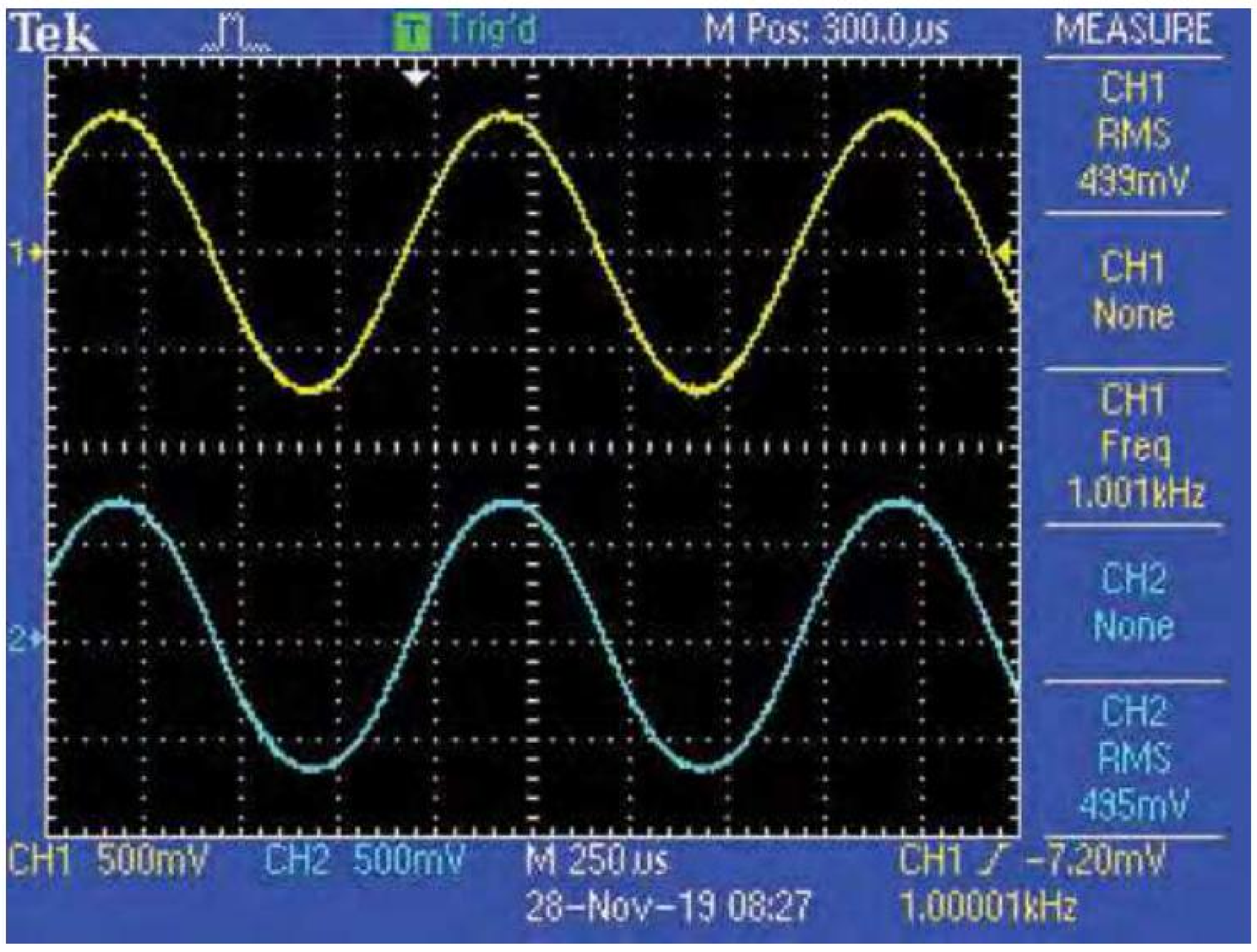
Fig.3: these PCB overlay diagrams show where all the parts go on both sides of the board. Note how the lever of microswitch S1 is touching jack socket CON2 (also see photos). And while potentiometers VR1-VR3 and VR5-VR7 look identical, and are all 10kΩ pots, some are linear and some are logarithmic, as described adjacent to the board. Be sure to orient the ICs, diodes, LEDs, electrolytic capacitors and RLY1 as shown here.

The half-supply rail (Vaa/2) is derived by two 10kΩ resistors in series across the Vaa supply. It is bypassed with a 100µF capacitor to remove supply noise, and buffered by unity-gain amplifier IC3a.

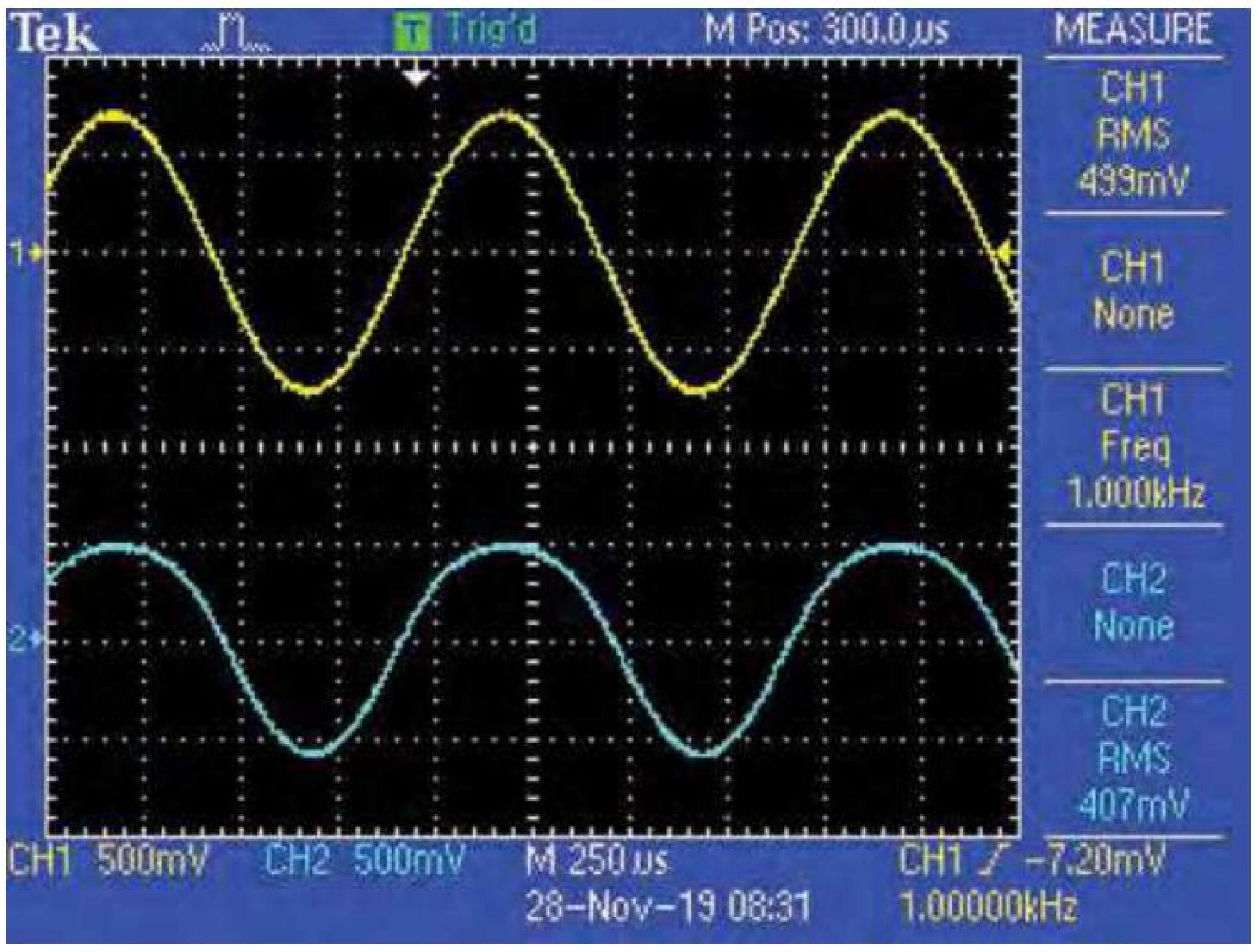
The output of IC1a is AC-coupled to the level control, VR1, which then feeds IC1b. IC1b provides 11-times gain. So when VR1 is at maximum, the output signal from IC1a is directly applied to the IC1b amplifier for an overall gain of 11.

With reduced settings for VR1, there is less overall gain from input to the output of IC1b.

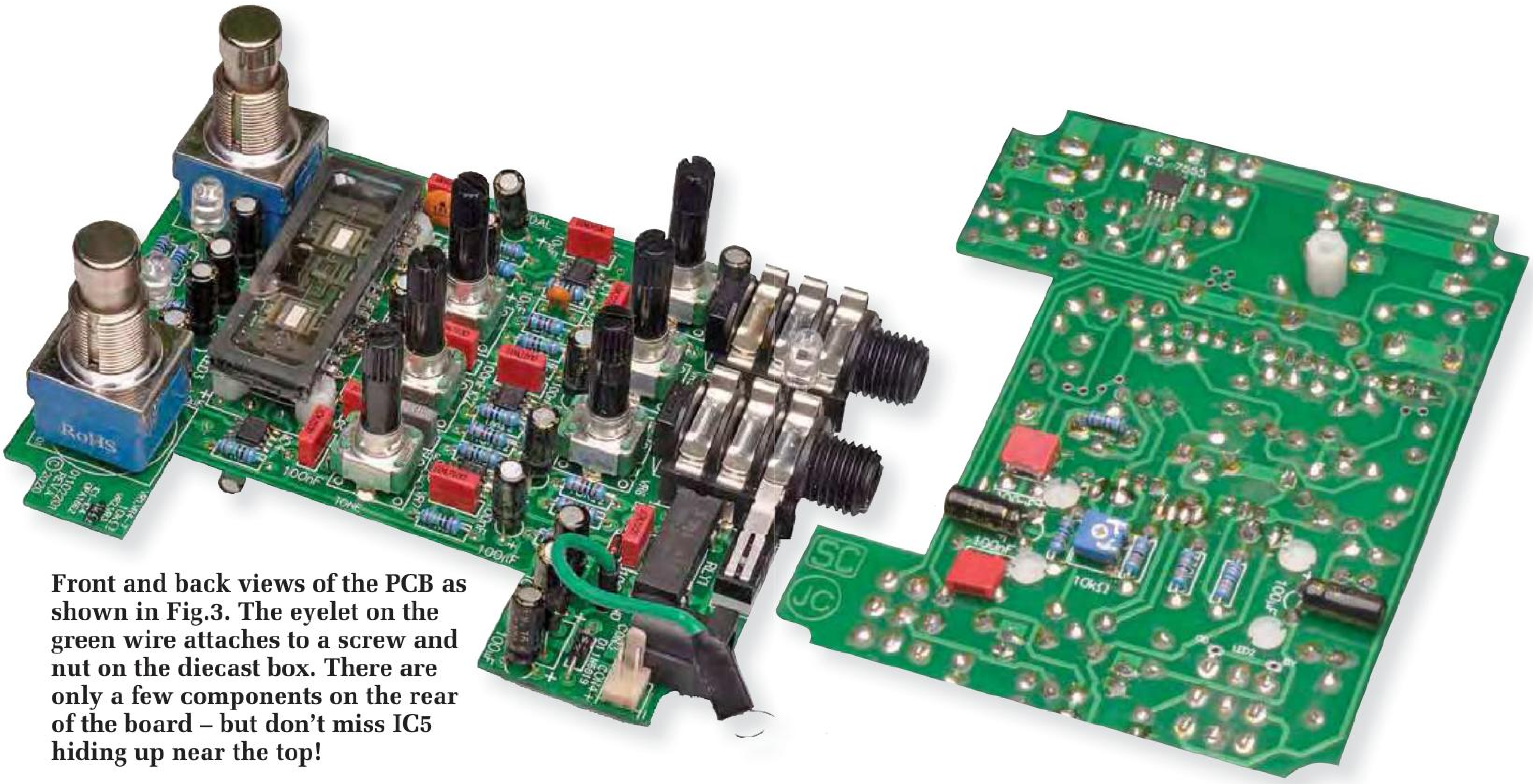
The signal from the output of IC1b drives the grid (G2) of Nutube V1b via a 10µF coupling capacitor. This grid is DC-biased via a 33kΩ resistor connected to the wiper of potentiometer VR2. VR2 is adjusted to set the operating point and hence, distortion produced by V1b. VR2's wiper voltage range is restricted to 1.27-3.3V by 8.2kΩ and 6.2kΩ padder


Tek
Trig'd
M Pos: 300.0µs
MEASURE
CH1 RMS 499mV
CH1 None
CH1 Freq 1.001kHz
CH2 None
CH2 RMS 495mV
CH1 500mV
CH2 500mV
M 250µs
CH1 ⁄ −7.20mV
28–Nov–19 08:27
1.00001kHz

Scope1: the input signal is shown at the top and the output signal at the bottom. Here the first distortion control is set for minimum distortion (mid-position), with the gain control set so that there is no overdrive. Therefore, the output waveform is similar to the input.


Tek
Trig'd
M Pos: 300.0µs
MEASURE
CH1 RMS 499mV
CH1 None
CH1 Freq 1.000kHz
CH2 None
CH2 RMS 407mV
CH1 500mV
CH2 500mV
M 250µs
CH1 ⁄ −7.20mV
28–Nov–19 08:31
1.00000kHz

Scope2: using the same settings as in Scope1, except that the first distortion control is rotated fully clockwise. The lower trace shows flat-topping of the sinewave for the positive portion of the waveform, which results in significant distortion.



Front and back views of the PCB as shown in Fig.3. The eyelet on the green wire attaches to a screw and nut on the diecast box. There are only a few components on the rear of the board – but don't miss IC5 hiding up near the top!

resistors. This provides a good range of distortion variation. The resistor values were chosen so that the centre position for VR2 provides the lowest distortion for V1b.

The amplified signal appears at the plate of V1b (A2). This has a 330kΩ load to Vaa via a 150Ω decoupling resistor. The supply is bypassed using a 100µF capacitor to remove supply ripple.

The high-impedance anode signal is again AC-coupled to another op amp buffer (IC2a) via a 100nF capacitor, biased to half supply with a 1MΩ resistor. This resistor loads the anode and so reduces the signal swing by about 25%. This is unavoidable in such a high-impedance circuit.

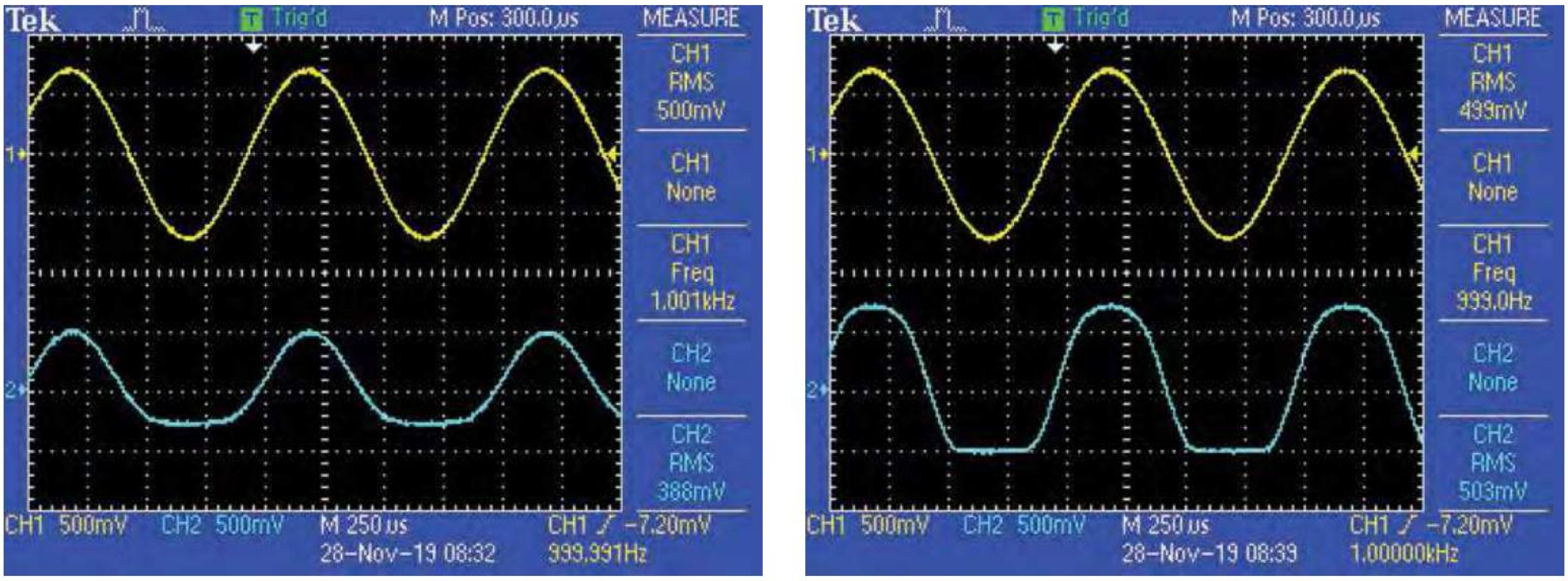
The output signal from IC2a goes to IC2b, a unity-gain inverter, which inverts the signal to compensate for the inversion by V1b. It also goes to the grid of V1a via trimpot VR4. The trimpot allows the signal to be attenuated (if desired) before being applied to the grid. V1a's grid bias is adjusted by potentiometer VR3 from 1.96-3.48V. These voltages are higher than for V1b for reasons explained below.

The output signal from the anode (A1) of V1a is buffered by IC3b, similarly to how IC2a buffers the output of V1b. The signals from both IC2b and IC3b drive level-adjustment potentiometers VR5 and VR6, respectively. The wipers of these potentiometers connect to either side of the boost switch, S3a. S3a therefore selects between the outputs of the first and second distortion stages.

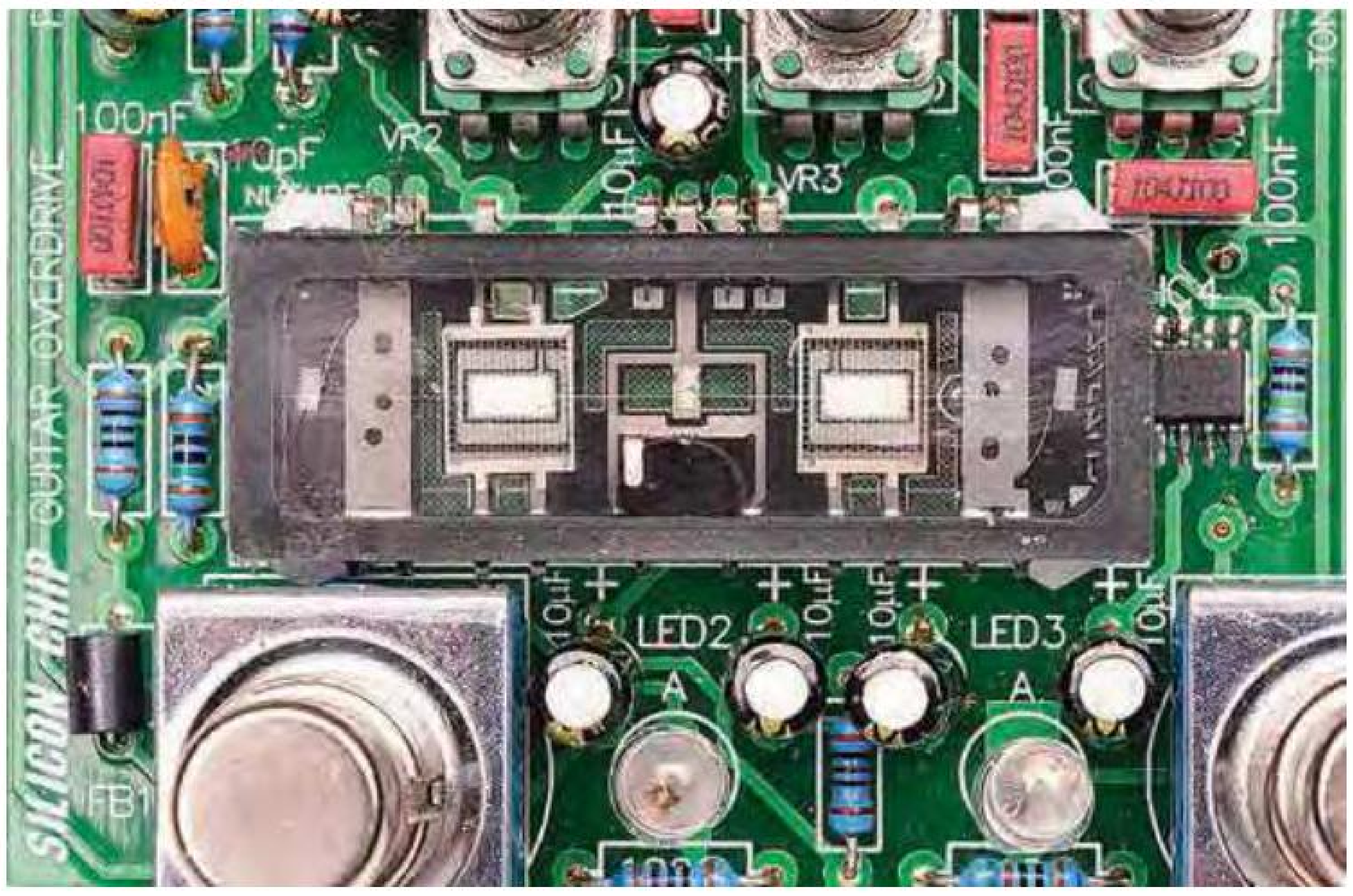
Note that in the second stage, triode V1a inverts the signal in the same way that op amp IC2b does. So both signals applied to S3a have the same phase. The signal selected by the boost switch is applied to buffer IC4b, ensuring that neither VR5 nor VR6 is unduly loaded. This buffer also provides a low impedance drive for the following tone control circuitry.

This comprises a simple low-pass filter with a corner frequency controlled by potentiometer VR7. The tone control provides a 20dB per decade (6dB/octave) roll-off of high frequencies. The roll-off (–3dB) point starts at about 23kHz when VR7 is fully anti-clockwise, so the tone control essentially does nothing. The roll-off frequency drops to about 2kHz when VR7 is wound fully clockwise. The resistance of VR7 and the 1kΩ fixed series resistor sets the RC time constant of the filter. The –3dB point can be calculated as $1/(2\pi RC)$, where C is 6.8nF, and R varies from 1-11kΩ.

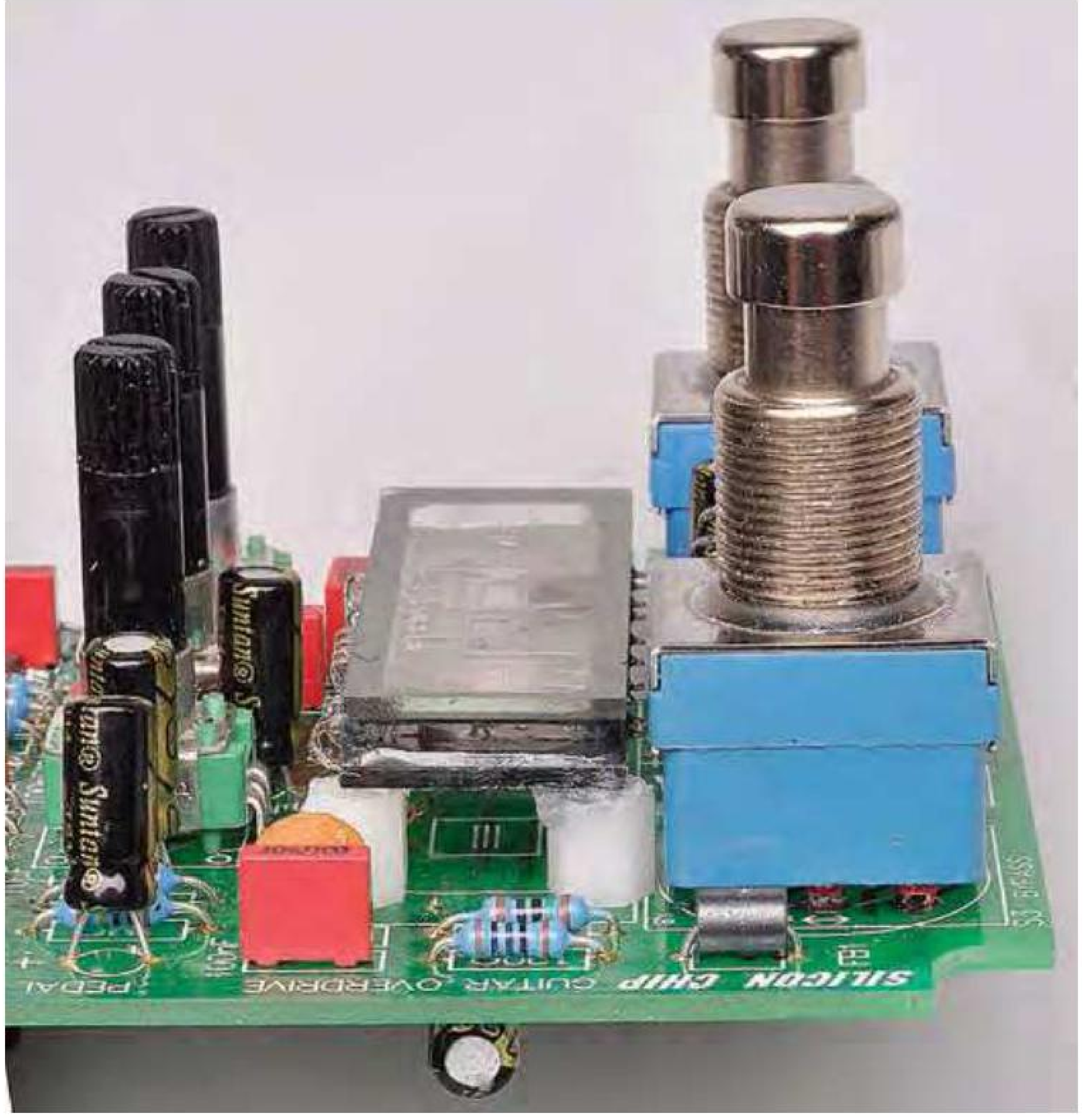
IC4a buffers the output of the tone control RC network. The signal from IC4a is then AC-coupled with a 100µF capacitor



Scope3 (left): the first stage distortion control is now set fully-anticlockwise. The top trace is the input signal, while the lower trace shows the flat topping (or is that bottoming?) of the sinewave on negative excursions. Scope4 (right): the gain is increased to set up an overdrive situation with the first distortion control set for minimum distortion (mid-way). The output level control is adjusted down to reduce the output signal level, compensating for the high gain at the input. Note how flat the negative portion of the waveform is; more signal would increase this and begin to flatten the positive portion.



The 6P1 valve mounts on four 6.3mm nylon standoffs, as shown in these photos. This helps minimise microphonics which could otherwise be a problem.



to remove the DC bias and is fed to bypass switch S2b, then through RLY1 and to output connector CON2. The output signal goes through a 100Ω isolation resistor to stop IC4a from oscillating should long (capacitive) leads be connected.

When S2 is set to the bypass position, the input signal at CON1 bypasses the distortion/overdrive circuitry, and the input to IC1a is tied to ground. This prevents switching noise when not bypassing, by keeping the 100nF capacitor at IC1a's input charged.

To prevent any audio noise when power is switched on and off, the output signal passes through the contact of relay RLY1, which is open when power is off. At power-on, the relay contact only closes after a delay, to allow time for the voltages in the circuit to stabilise. More on this later.

Filament current

Like most thermionic valves, the Nutube has heater filaments. There is one for each triode, between the pins labelled F1 and F2 for V1a and between F2 and F3 for V1b. These filaments are connected in series, with F2 being the junction.

There are two ways of driving these filaments. Current can be supplied to F1 and F3 via separate resistors with F2 tied to ground. In this case, 17mA flows through each filament for a total of 34mA. Or, like in our circuit, F1 or F3 can be connected to ground and current is supplied to the opposite end of the pair of filaments, so the same 17mA flows through both, halving the total current requirement.

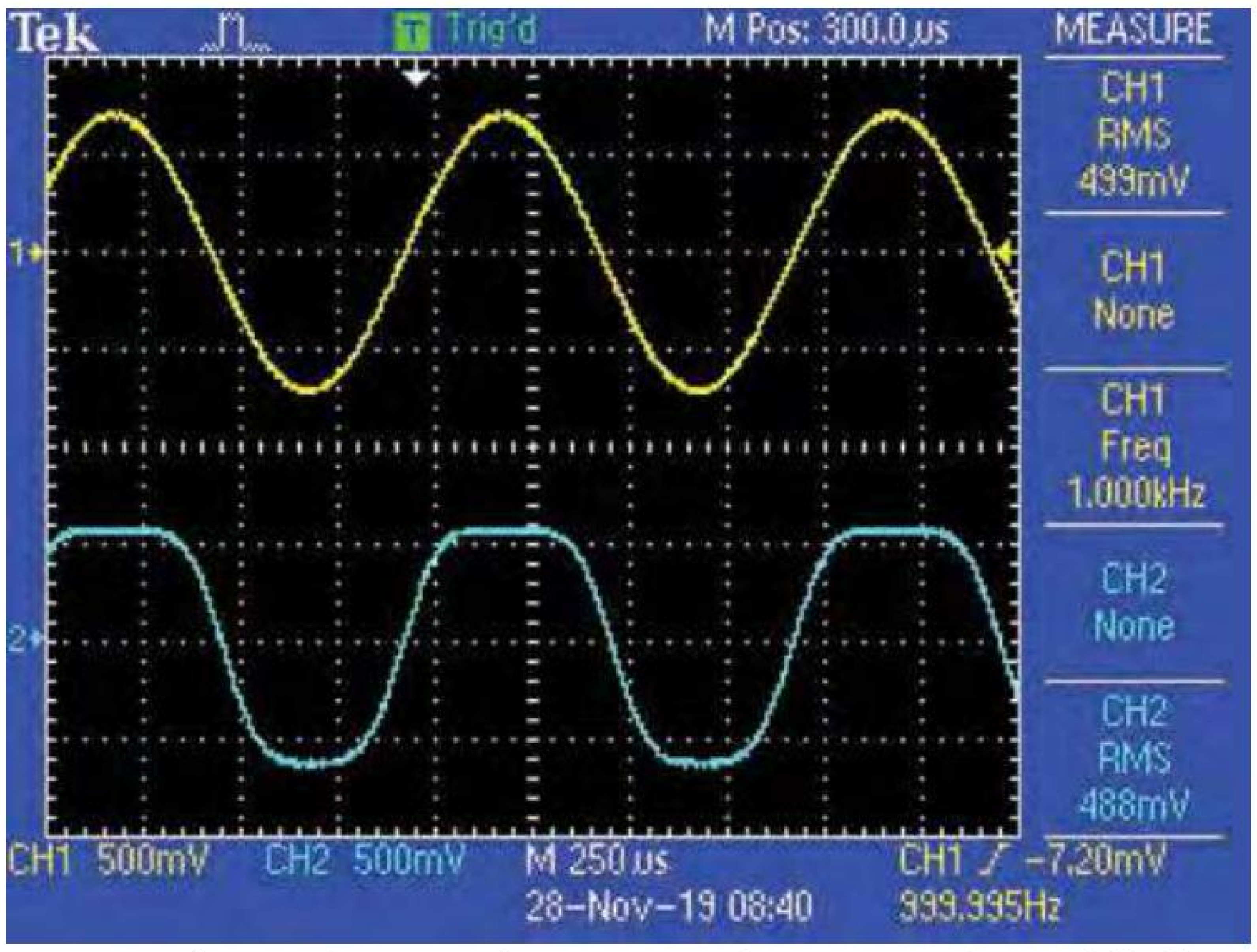
The latter is more efficient and enhances battery life. In our circuit, F3 is tied to ground, F2 is effectively open (with just a bypass capacitor connected) and current supplied via a 200Ω resistor from 5V to F1. F1 is also bypassed with 10µF capacitor, which forms an RC low-pass filter with the 200Ω resistor. These two capacitors reduce noise in the circuit.

The disadvantage of connecting the filaments in series is that, due to the voltage drop across the filaments, the cathode of one triode will sit at 0.7V rather than 0V. This means that the two triodes need 0.7V different grid bias voltages to operate in the same manner. This is the reason for the different grid-voltage adjustment ranges for potentiometers VR2 and VR3, due to their different padder resistors.

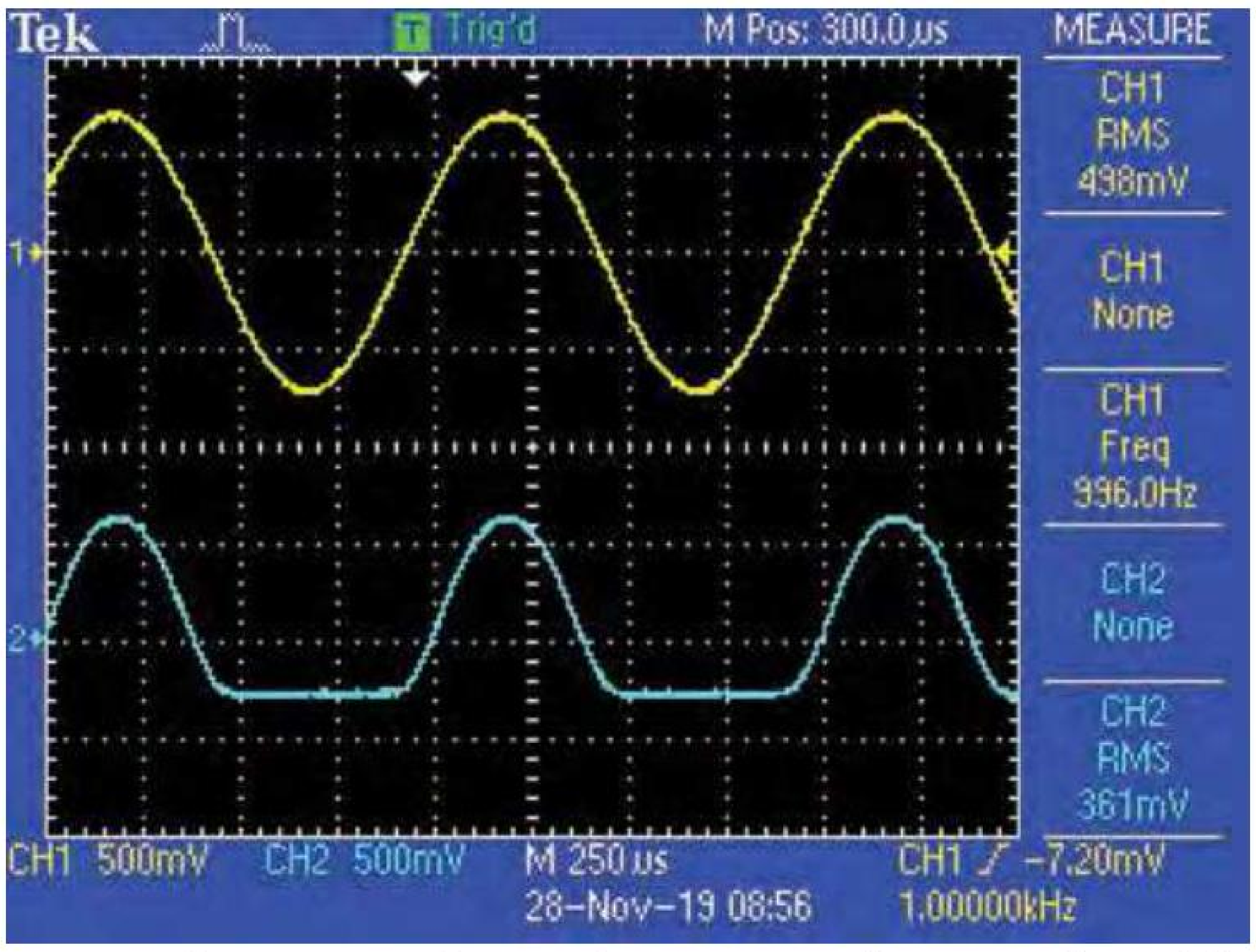
Indicators LED1-LED3 are powered from the 5V supply via 510Ω resistors. LED1 is the power indicator, and it runs off the 5V rail. The bypass (LED2) and boost (LED3) LEDs are only powered when the bypass and boost switches are on.

Power supply

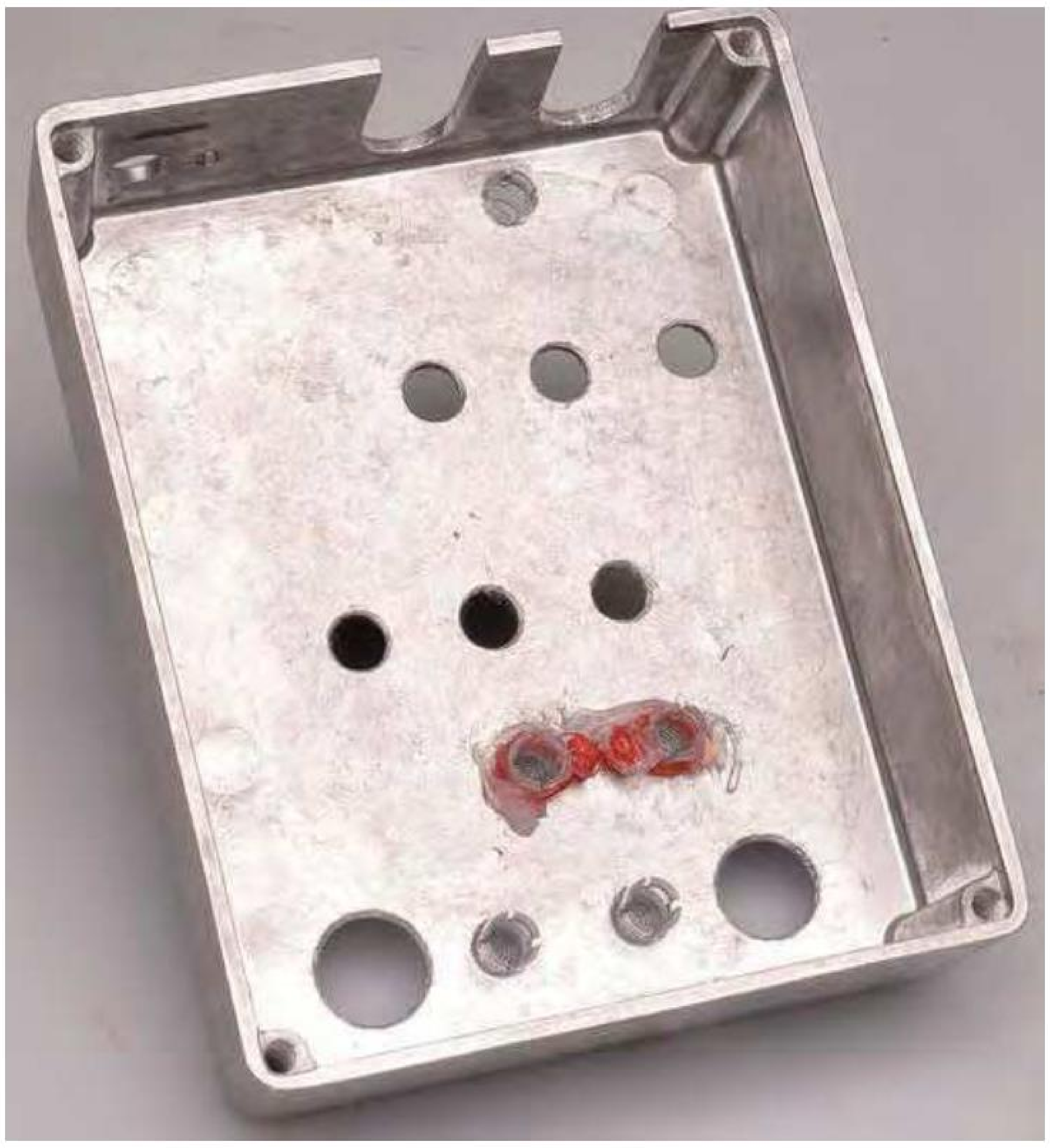
The circuit powers up when microswitch S1 is activated by a jack plug being inserted into CON2. The plug pushes



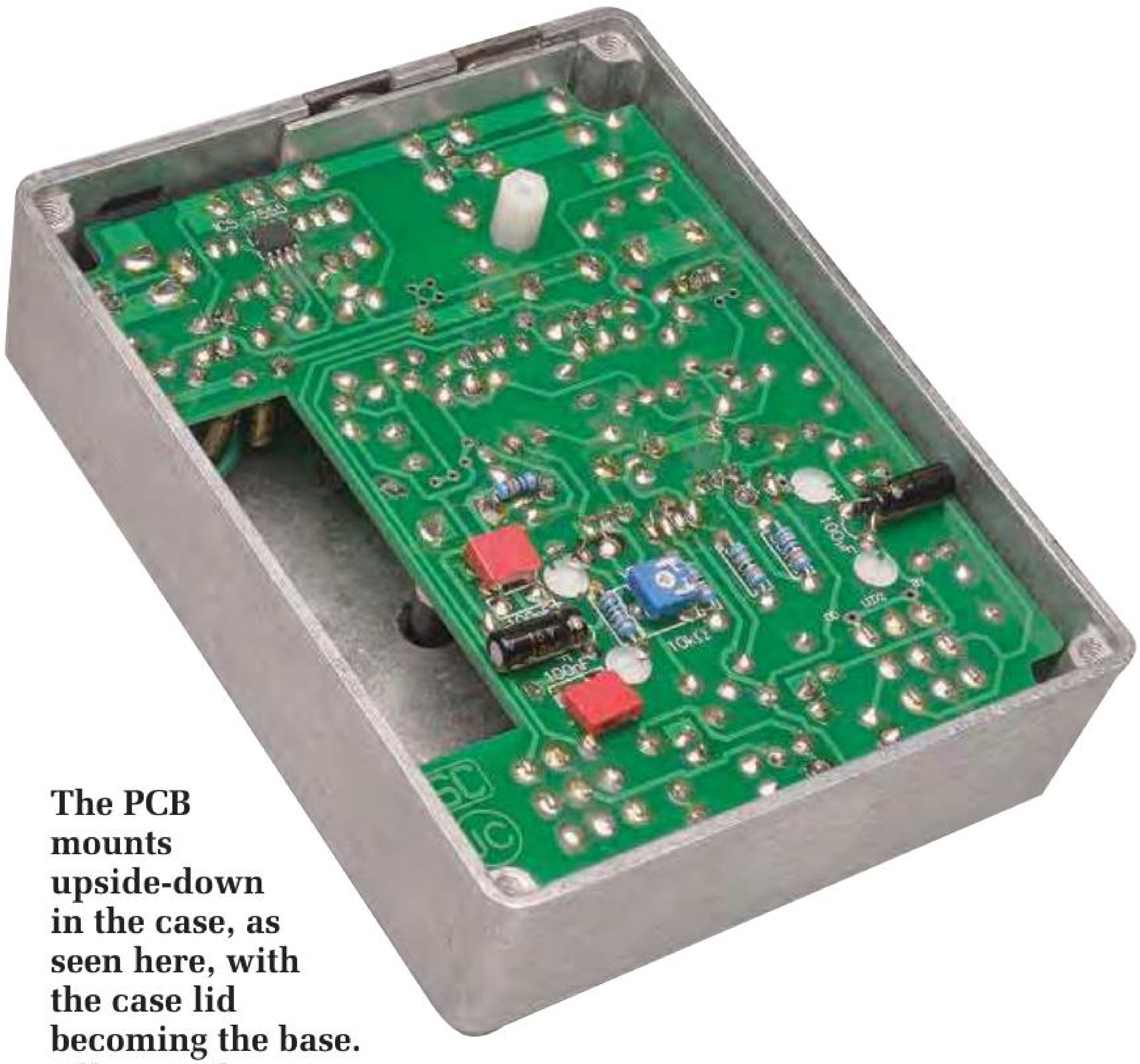
Scope5: the settings as the same as in Scope4, but with the Stage1 distortion control set fully clockwise. This produces a more square form of overdrive; the incoming sinewave is being converted into a sort of rounded square wave.



Scope6: the same settings as in Scope4 and Scope5, but with the first distortion stage control set fully anti-clockwise. The output waveform is now very flat on negative excursions but mostly undistorted on positive excursions.



14 holes and two slots are drilled/cut in the diecast case. Note these holes are in the bottom and end of the case. (See dimensioned drilling diagram on page 36).



The PCB mounts upside-down in the case, as seen here, with the case lid becoming the base. All controls emerge through what was the base – which is now the front panel. Five bezels in the panel show the status of the LEDs and 6P1 Twin Triode.

on the ground pin in CON2, and this lifts the microswitch actuator to power the circuit. This is a slightly unconventional method of switching power, but it works reliably.

We decided to do it this way, rather than using a PCB-mount jack socket with an isolated internal switch or a panel-mount wired socket, mainly because those socket types are not universally available, while the type we are using is.

When there is no DC plug inserted, the DC socket (CON3) connects the negative end of the battery to ground, so the circuit will be powered from the battery when S1 is closed. When a power plug is inserted, the battery negative is disconnected, and the unit runs from the DC power supplied to CON3. In either case, schottky diode D1 prevents damage if the battery or DC power plug polarity is incorrect.

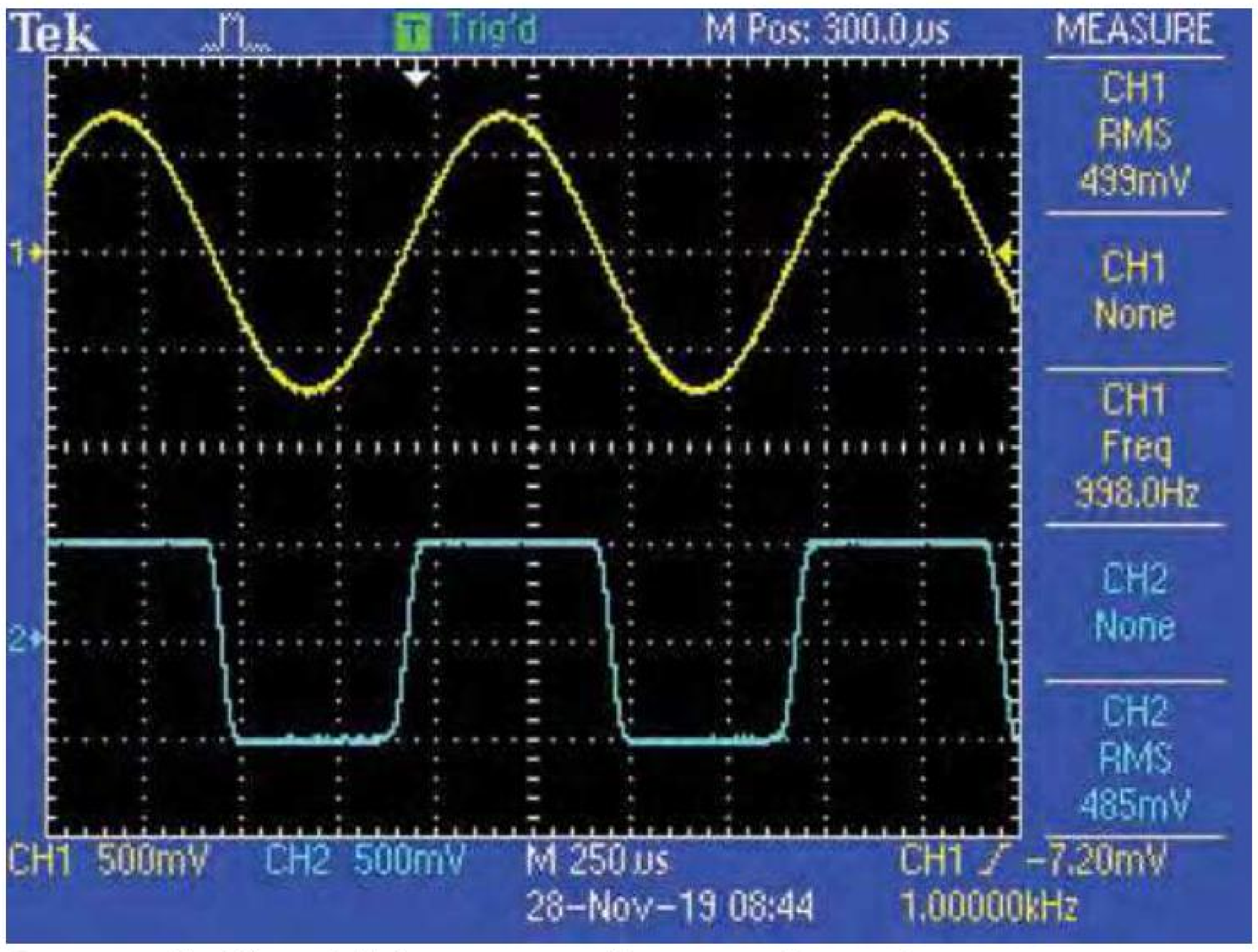
REG1 is a low-dropout, low quiescent current 5V linear regulator. Its main purpose is to maintain a constant grid voltage for the Nutube triodes and a constant voltage for the filaments. It also supplies power to 5V relay RLY1. A 100µF capacitor bypasses the input supply to REG1, and its output voltage is filtered similarly.

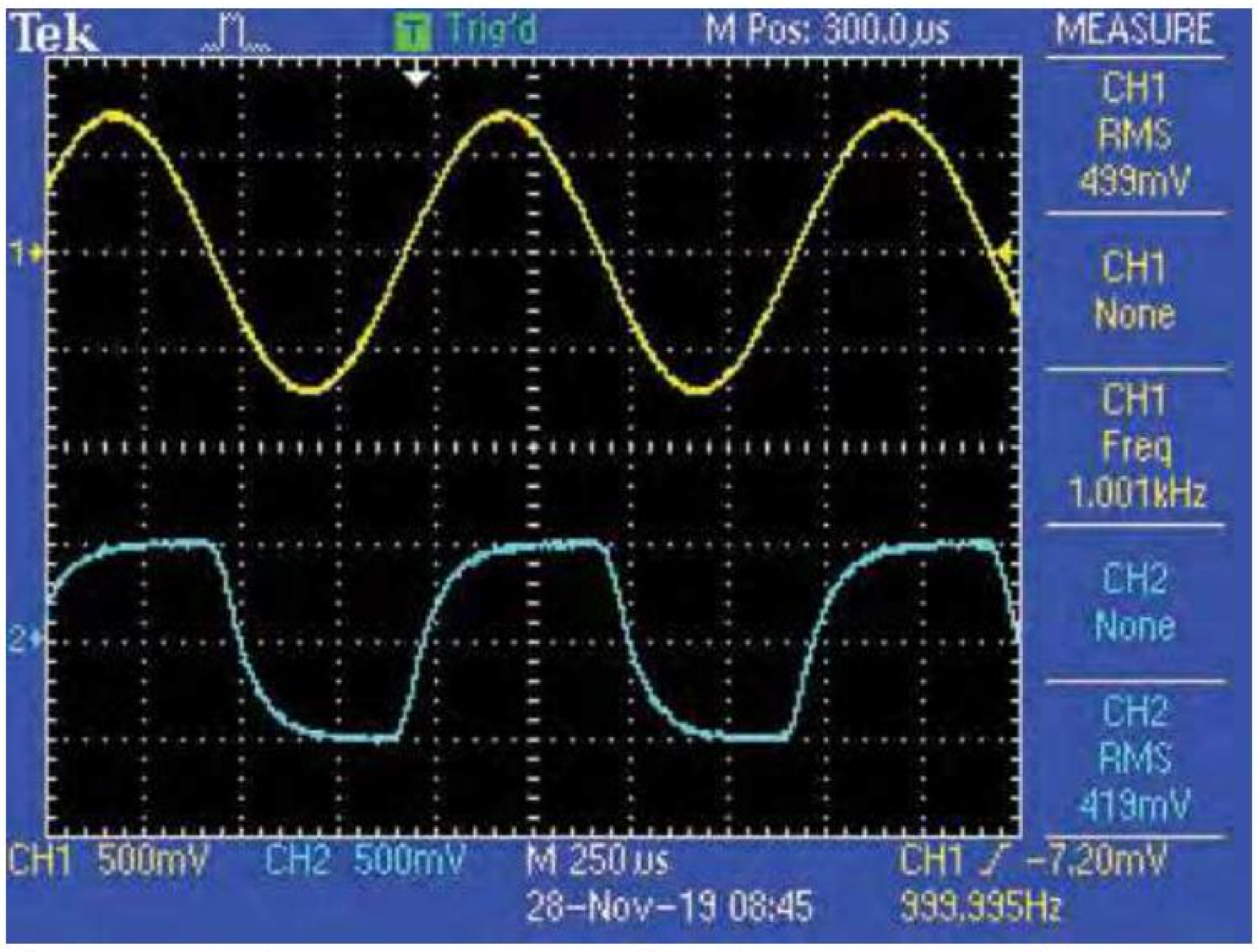
Relay delay

As mentioned, RLY1 switches on after a delay when power is first applied. IC5, a CMOS version of the 555 timer, provides this delay. When power is first applied, the 10µF capacitor at its trigger input (pin 2) and threshold input (pin 6) is discharged. The pin 3 output is at 5V, which drives the bottom end of the relay. There is no voltage across the relay coil, so it is off.

When the 10µF capacitor charges to 66% of the 5V supply (3.33V), the threshold voltage is reached and the pin 3 output goes low, energising the relay coil.

RLY1 is a reed relay with a meagre 10mA coil current requirement, so IC5 can drive the coil directly. Diode D2





Scope7 (left): with boost on, the waveform is now so overdriven and limited that the output waveform is almost square. Scope8 (right): this shows the effect of the tone control when set for maximum high-cut. The settings are the same as in Scope7, except for the tone control. Note the difference between the squared waveform in Scope7 and the rounded off surf-wave-like effect here, due to the operation of the tone control.

Parts list – Nutube Guitar Effects Pedal

1 double-sided PCB coded 01102201, measuring 86 × 112mm
1 panel label
1 119 × 94 × 34mm diecast enclosure [Jaycar HB5067]
1 Korg Nutube 6P1 double triode thermionic valve (V1) [RS Components 144-9016]
2 6.35mm PCB jack sockets (CON1,CON2) [Jaycar PS0195]
1 2-pin PCB-mount header with 2.54mm spacing (CON4)
  [Jaycar HM3412, Altronics P5492]
1 PCB-mount DC power socket (CON3) [Jaycar PS0520, Altronics P0621A]
1 2-pin polarised header plug [Jaycar HM3402, Altronics P5472 + 2 x P5470A]
1 C&K ZMA03A150L30PC microswitch or equivalent (S1) [eg, Jaycar SM1036]
2 3PDT footswitches (S2,S3) [Jaycar SP0766, Altronics S1155]
1 5V DIL reed relay (RLY1) [Jaycar SY4030, Altronics S4100]
6 11.5mm diameter 6mm tall 18-tooth spline knobs
  [RS Components 299-4783] (see text)
1 4mm OD, 5mm-long ferrite bead (FB1) [Altronics L5250A, Jaycar LF1250]
5 5mm clear LED bezels [RS Components 171-1931]
1 6.3mm mono jack plug or jack plug lead (to test power switching)
1 9V battery
1 9V battery clip lead
1 9 x 45mm piece of 1-1.5mm-thick aluminium sheet
1 PC stake (GND)
1 solder lug (for grounding enclosure)
4 stick-on rubber feet OR
4 M4 x 10mm nylon screws – see text
4 6.3mm-long M3 tapped nylon spacers (to go under Nutube)
4 M3 x 6mm nylon or polycarbonate screws (for Nutube spacers)
1 9mm-long M3 tapped nylon spacer (support for PCB)
2 M3 x 6mm screws (for solder lug and 9mm spacer)
1 M3 nut and star washer (for solder lug)
1 160mm length of 0.25mm diameter enamel copper wire
1 50mm length of green medium duty hookup wire
2 100mm cable ties

Semiconductors
4 OPA1662AID dual op amps, SOIC-8 (IC1-IC4) [RS Components 825-8424]
1 ICM7555CBA CMOS timer, SOIC-8 (IC5)
1 1N5819 1A schottky diode (D1)
1 1N4148 small signal diode (D2)
1 LP2950CT-5.0 5V LDO regulator (REG1)
3 5mm high-intensity LEDs (one green and two red recommended)

Capacitors
6 100µF 16V PC electrolytic
10 10µF 16V PC electrolytic
11 100nF MKT polyester
1 6.8nF MKT polyester
1 470pF ceramic
1 100pF ceramic

Resistors (all 0.25W, 1% metal film)
6 1MΩ   1 470kΩ   2 330kΩ   1 33kΩ   1 13kΩ   7 10kΩ
1 8.2kΩ   1 6.2kΩ   1 1kΩ   3 510Ω   1 200Ω   1 150Ω   2 100Ω
1 20kΩ miniature horizontal trimpot (VR4) [Altronics R2481B, Jaycar RT4362]
3 10kΩ vertical 9mm log (A) pots (VR1,VR5 and VR6) [Altronics R1958]
3 10kΩ vertical 9mm linear (B) pots (VR2,VR3 and VR7) [Altronics R1946]

Miscellaneous
Solder, solder wick, clear neutral-cure silicone sealant (eg, roof and gutter silicone)

shunts the back-EMF voltage from the coil when RLY1 is switched off.

Note that RLY1 prevents a bypass signal from getting to the output when the *Pedal* is powered off. However, since power is switched on automatically when a plug is inserted into output connector CON2, and you can't get a signal from the unit without anything plugged into CON2, this is not a big problem.

The infill piece we made to cover the slots (as seen opposite). Fig.4 (below) shows the dimensions.

Construction

The *Overdrive and Distortion Pedal* is built using a double-sided PCB coded 01102201, measuring 86 × 112mm and available from the *PE PCB Service* at: **www.electronpublishing.com**

It is housed in a diecast enclosure measuring 119 × 94 × 34mm. Fig.3 shows the PCB assembly details.

Begin by fitting the surface-mounting parts on the top side of the PCB, ie, IC1-IC4, followed by IC5 on the underside. These are not difficult to solder using a fine-tipped soldering iron.

Good close-up vision is necessary; you may need to use a magnifying lens or glasses to see well enough.

Make sure that these components are oriented correctly before soldering in place. Also, check that IC5 is the 7555 timer. For each device, solder one pad first and check its alignment.

Adjust the component's position by reheating the solder joint if necessary before soldering the remaining pins. If any of the pins are bridged by solder, use solder wick to remove it.

Note that adjacent pins 1 and 2 of IC1, IC2, and IC4 and pins 6 and 7 of both IC3 and IC4 connect together on the PCB, so a solder bridge between these pins is acceptable.

Continue construction by mounting the resistors on the top side of the PCB (use your DMM to check the values), followed by the ferrite bead (FB1). Feed a resistor lead off-cut through the bead and bend the lead to fit the PCB pads. Push the bead lead down so that it sits flush against the PCB before soldering its leads.

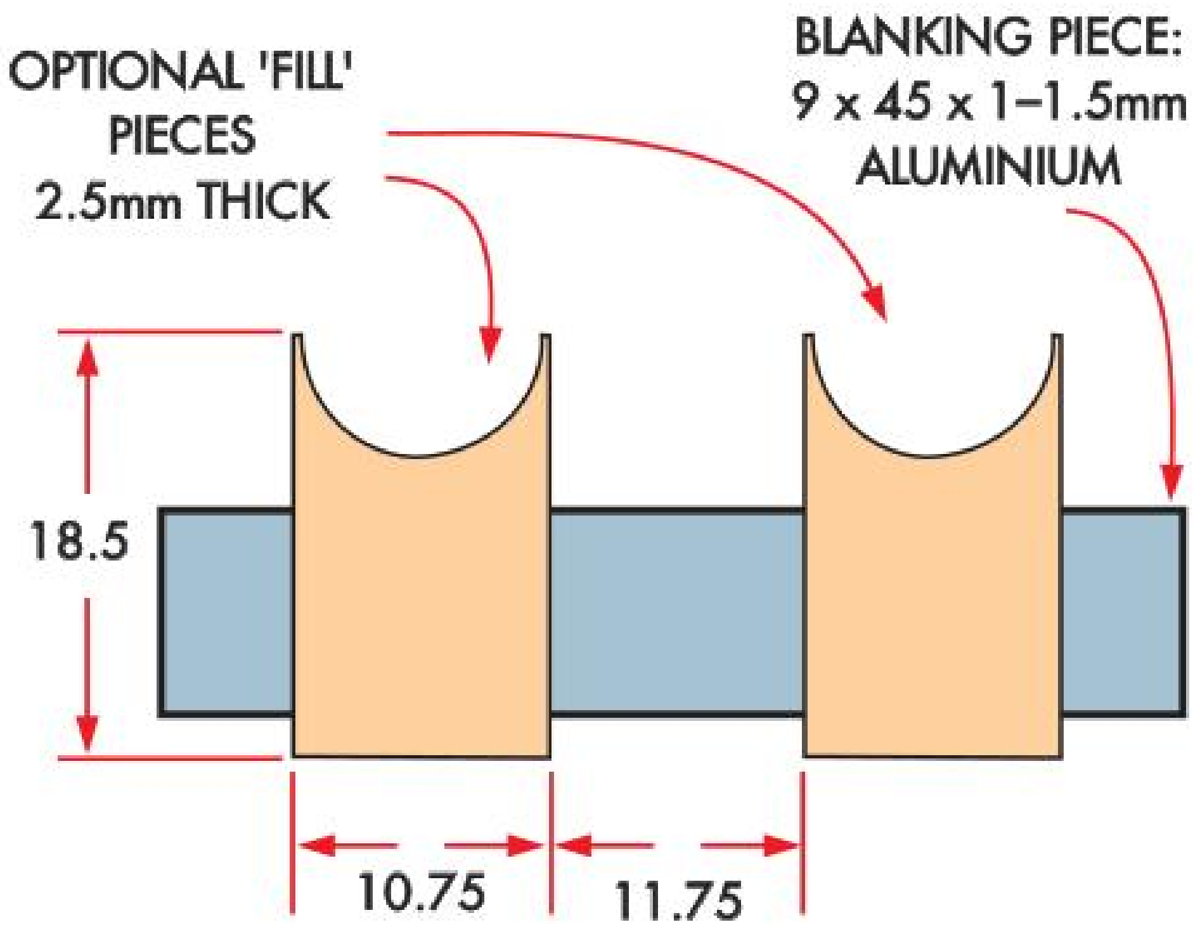
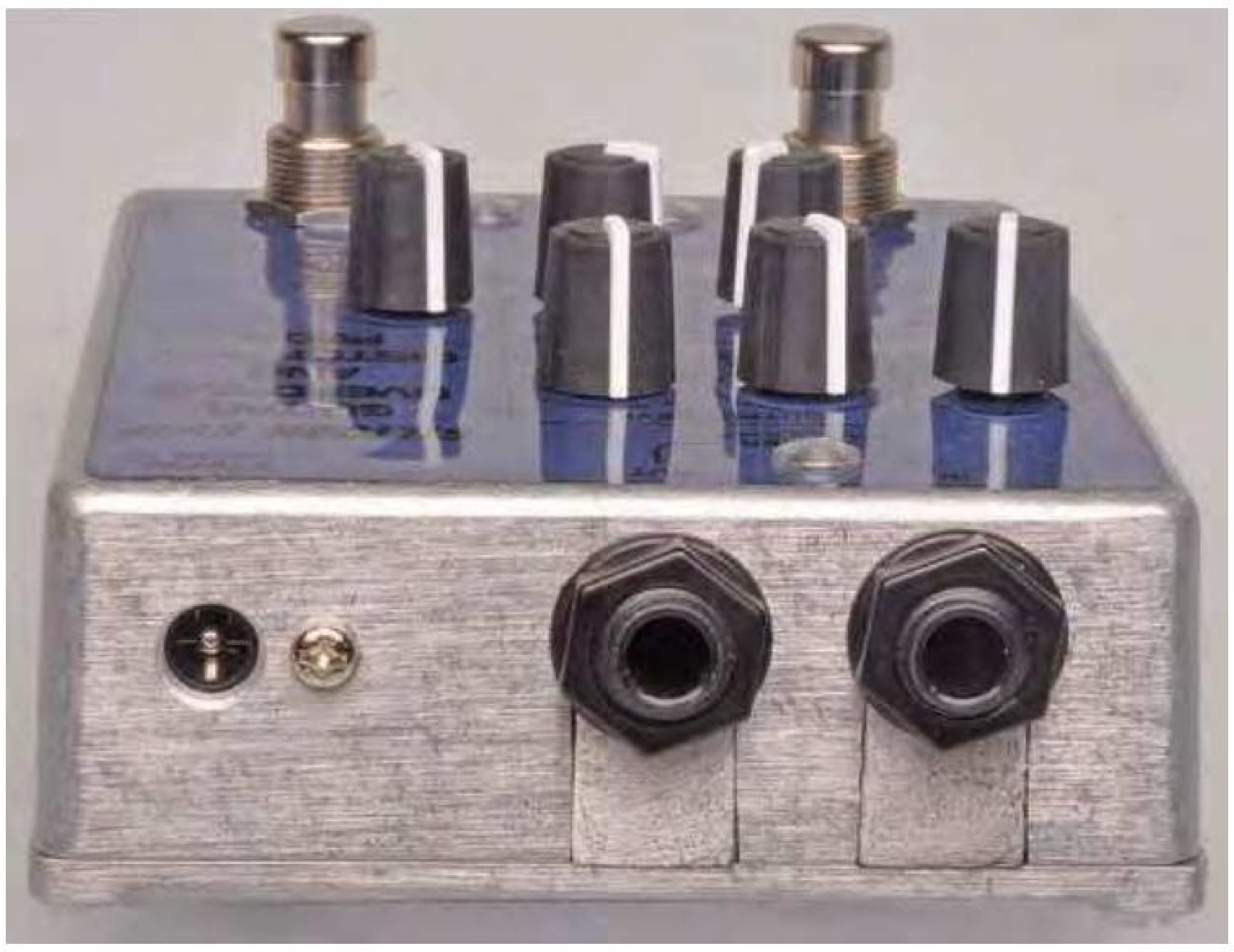
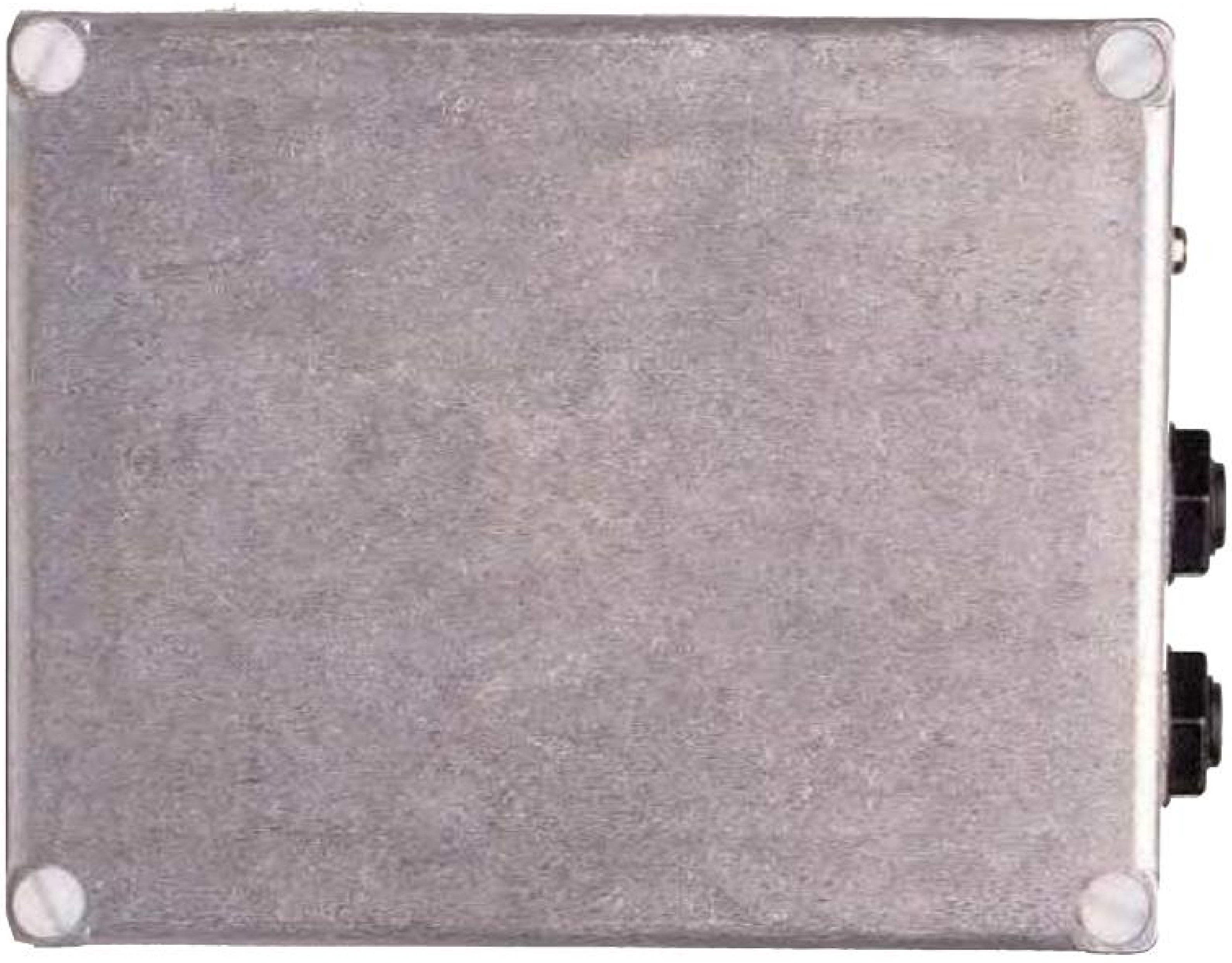

OPTIONAL 'FILL' PIECES 2.5mm THICK
BLANKING PIECE: 9 x 45 x 1–1.5mm ALUMINIUM
18.5
10.75
11.75

Fig.4: cut a piece of aluminium as shown to partially cover the slots, with the two optional plastic pieces glued to it to fully cover those spaces.



The 6.35mm input and output sockets need to be slid into place which necessitates slots, rather than holes (see the drilling photo on the next page). We fashioned an infill piece from scrap aluminium (seen opposite) the same size as the slots, held in place by the sockets themselves and their washers/nuts.



(Right): rather than glue feet on the lid of the case (which becomes the base) we used four M4 nylon pan-head (round-topped) screws which act as pretty robust feet, their heads being slightly proud of the surface. We reasoned that glue-on feet probably wouldn't last long in use but the screws should last.

The resistors that mount on the underside of the PCB can be installed now. Solder these from the top side of the PCB and trim the leads close to the PCB. Diodes D1 and D2 can then be mounted – note they are different types. Take care to orient them correctly.

Now fit the MKT and two ceramic capacitors, followed by the electrolytic capacitors, which are polarised. Their longer leads go to the pads marked with a '+' on the PCB. The two 100nF and two 100µF capacitors that mount on the underside of the PCB need to lie on their sides.

Next, install trimpot VR4 on the underside, soldering its pads on the top side. VR4 might be marked as '203' rather than '20kΩ'.

Follow with potentiometers VR1-VR3 and VR5-VR7, noting that VR1, VR5, and VR6 are logarithmic types (marked 'A') and VR2, VR3 and VR7 are linear types (marked 'B'). These pots may be labelled as '103' instead of '10kΩ'.

The next step is to fit REG1 by splaying its leads slightly to fit the hole arrangement on the PCB. Also, install the PC stake at the GND test point. The locking header for the battery lead can be fitted now, then RLY1, the two jack sockets and the DC socket.

Switch S1 is mounted so that the lever is captured under the front sleeve contact of the CON2 jack socket. We have provided slotted holes so the switch can be inserted and slid, so the lever enters under the contact.

Check that the switch is open circuit, between the two outside pins, when there is no jack plug inserted. There must be continuity between the two outside pins when a jack plug is inserted.You may need to bend S1's lever a little so that the switch works reliably.

Mount foot switches S2 and S3 now. Make sure these are perfectly vertical before soldering their pins. The LEDs are mounted later when the PCB is installed in its case.

Wiring

The Nutube is mounted with its envelope parallel to the PCB. Its leads are soldered to the pads on top of the PCB using short lengths of enamelled copper wire. This wire helps prevent microphonics in the Nutube, by giving a flexible connection.

Bend the Nutube leads back under the body and solder 20mm lengths of the 0.25mm enamelled copper wire to each Nutube lead. Note that molten solder held over the end of the wire will burn off the enamel so that the wire can be soldered.

There are two leads for F1 and two leads for F3 at each end of the Nutube. The two leads are connected together, so only one wire is needed to connect each pair to the PCB.

Fix the four 6.3mm nylon spacers to the PCB under where the Nutube mounts, using nylon or polycarbonate screws.

Place small dobs of neutral-cure silicone sealant on top of each spacer, then sit the Nutube on top. There should be a 1mm silicone bead between each spacer and the underside of the Nutube envelope. Ensure the Nutube is correctly positioned and wait for the silicone to cure.

The next step is to cut the battery wires to 60mm long, then crimp or solder them to the polarised plug pins. Insert these terminals into the plug shell, making sure you get the red and black wires in the correct position for polarity: '+' to red and '–' to black.

A grounding wire is required to connect the case to the GND terminal on the PCB. This prevents hum injection to the circuit via the enclosure. Solder the wire to the lug at one end and the GND terminal at the other.

Heatshrink tubing can be used over the lug terminal and the GND PC stake. When assembled, the solder lug is secured to the case using M3 x 6mm screw, star washer and M3 nut.

Powering up and testing

If you are planning to use a battery, connect it now. Alternatively, plug in a 9-12V DC supply to CON3. Insert a jack plug into CON2 to switch on the power.

Set your multimeter to read DC volts, connect the negative probe to the GND terminal and measure the regulator input and output voltages. The input should be about 0.3V below the DC supply. The regulator output should be between 4.95V and 5.05V.

Also, check that RLY1 switches on after about five seconds. You should hear a quiet click.

Centre VR2 so that the left-hand plate of the Nutube lights up at its brightest. Similarly, adjust VR3 so the right-hand plate of the Nutube glows brightest. Note that when the signal passes through the unit, the plate glow will dim a bit. Set VR4 fully clockwise for now.

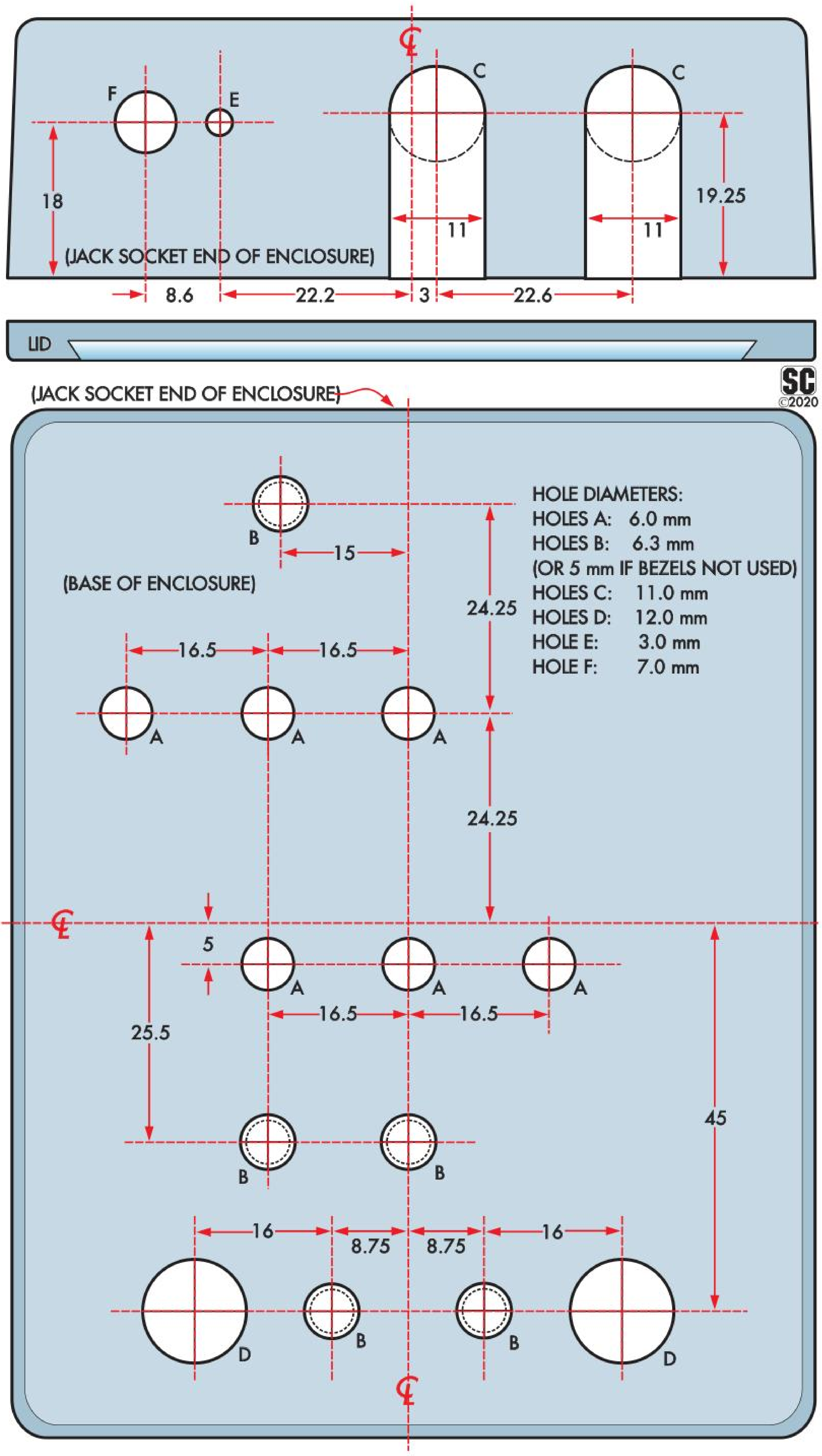

F
E
C
C
18
19.25
11
11
(JACK SOCKET END OF ENCLOSURE)
8.6
22.2
3
22.6
LID
(JACK SOCKET END OF ENCLOSURE)
SC
©2020
HOLE DIAMETERS:
HOLES A: 6.0 mm
HOLES B: 6.3 mm
(OR 5 mm IF BEZELS NOT USED)
HOLES C: 11.0 mm
HOLES D: 12.0 mm
HOLE E: 3.0 mm
HOLE F: 7.0 mm
(BASE OF ENCLOSURE)
B
15
24.25
16.5
16.5
A
A
A
24.25
5
A
A
A
16.5
16.5
25.5
45
B
B
16
8.75
8.75
16
D
B
B
D

Fig.5: drill the holes in the enclosure base and side as shown. Two of the holes in the side need to be slotted so that the sockets can slide down into place. The only hole required in the lid is optional, to access VR4; use the PCB to locate this hole if you've decided to drill it. (You can download this guide from the March 2021 page of the *PE* website.)

Housing it

We use the lid of the diecast enclosure as the base, and the main body becomes the top. The drilling diagram (Fig.5) shows where holes are made in the base and side of the case, and can also be used as a template. Holes are required for the potentiometer shafts, LED bezels, Nutube viewing holes and the footswitches on the main panel area.

Cut-out slots are also required for the two jack sockets and DC power inlet, at the end of the box. Slots, rather than holes, are required so that the jack sockets can be manoeuvered into place.

To stop dirt and other gunk from entering the case we made a 45mm x 9mm blanking piece from a sheet of 1-1.5mm thick aluminium. This covers the slots from the inside, after the jack sockets have been inserted. We also added some shaped plastic pieces to fill the slots to the same level as the outside of the enclosure.

This is optional; the fill pieces can be glued to the backing piece, as shown in the drawing and photograph.

It's a good idea to add rubber feet so it won't move during use. While you could apply stick-on rubber feet to the lid, we weren't convinced they would stay stuck on during the rough and tumble of use.

So we replaced the original lid securing screws with Nylon M4 panhead screws instead. The heads are proud of the surface by a couple of millimetres and hence act as the feet. However, to allow this, the holes in the enclosure for the original mounting screws had to be drilled out to 3.5mm then tapped using an M4 tap.

Fig.6 shows the lid panel artwork we have prepared for the *Pedal*. It can be downloaded from the March 2021 page of the *PE* website and printed out (the download also includes the drilling templates).

To help protect it, you can print the label onto overhead projector film as a mirror image, so the ink will be between the enclosure and film when affixed. Use projector film that is suitable for your printer (either inkjet or laser) and affix using clear neutral-cure silicone sealant. Squeegee out the lumps and air bubbles before the silicone cures. Once cured, cut out the holes through the film with a hobby or craft knife.

Mounting the PCB

Attach the 9mm M3 tapped spacer to the rear of the PCB using an M3 screw through the top. The hole is located between CON1 and CON2. This spacer keeps the PCB in place by resting on the lid when the case is assembled.

If you haven't already done so, solder the ground to the GND PC stake on the top of the PCB and shrink a short length of heatshrink tubing over the stake. The ground lug mounting position is adjacent to the DC socket. Secure this using an M3 screw, star washer and nut before the PCB is inserted into the case.

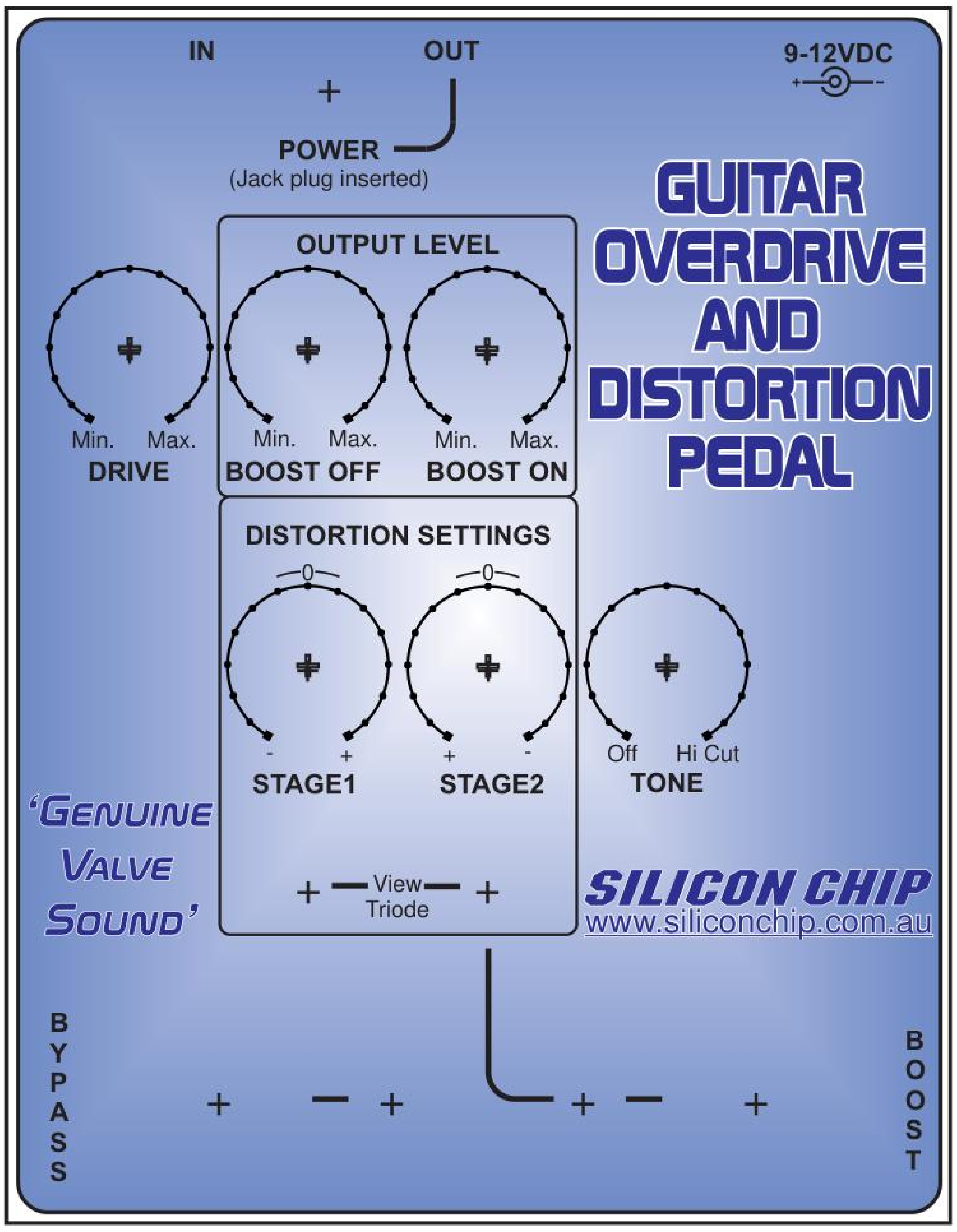

IN
OUT
9-12VDC
POWER
(Jack plug inserted)
OUTPUT LEVEL
Min. Max.
DRIVE
Min. Max.
BOOST OFF
Min. Max.
BOOST ON
GUITAR OVERDRIVE AND DISTORTION PEDAL
DISTORTION SETTINGS
0
0
- +
STAGE1
+ -
STAGE2
Off Hi Cut
TONE
'Genuine Valve Sound'
View Triode
SILICON CHIP
www.siliconchip.com.au
BYPASS
BOOST

Fig.6 (right): same-size front panel artwork which fits on the bottom of the diecast case (which of course becomes the top). It's easiest to cut the holes once the panel has been glued in position. Note our comments re longevity of this panel – it's likely to suffer some pretty rough treatment! (Download from the March 2021 page of the *PE* website.)

Orient the solder lug so that the wire is closest to the enclosure's base and so does not foul any components on the PCB.

Insert the LED bezels from the outside of the case. The Nutube viewing holes also require bezels to stop dirt and dust from getting in. They can be held in place with small cables ties, pressing them against the inside of the enclosure, then glued in place with silicone sealant.

Before putting the PCB into the enclosure, insert the LEDs into the PCB holes. The longer anode leads must go into the holes marked 'A' on the PCB. Place the nylon washers for the footswitches onto each switch shaft, then fit the PCB into the enclosure. Push the LEDs into position in their bezels to capture them, then solder the LED leads from the rear of the PCB.

The battery compartment is made from a rectangular cutout on the PCB. The battery can be prevented from moving by packing some of the foam packaging supplied with the Nutube around it.

Insert this between the end of the battery and the edge of the PCB. If you are not using a battery, unplug the battery clip from CON3 and remove it to prevent the contacts from shorting against the board.

Knobs

Since the potentiometer shafts do not protrude much more than 9mm above the lid, you can't use standard knobs with a skirt. The skirts are intended to cover the potentiometer securing nut but there is no nut here, resulting in insufficient internal fluting to secure the knobs to the shafts.

There are two ways around this; either use knobs without a skirt, or cut the skirts off. The knobs mentioned in the parts list don't have skirts.

If you can't get those for some reason, you can purchase Jaycar knobs in the HK7730-7734 range (we recommend Cat HK7733 blue) and cut the lower skirt flange off with a hacksaw.

Finally, secure the lid in place using either the original screws or nylon M4 screws, as mentioned previously. Attach the rubber feet to the base using their sticky-back adhesive if you are not using the nylon screws as feet.

Removing the knobs

The knobs may be difficult to remove by pulling; you may need to lever them off. Insert a sheet of thin plastic between the lever (eg, a flat-bladed screwdriver) and the case to prevent damage to the panel.

Using it

It's basically just a matter of twiddling the controls until you get the sound you want. The only control which is not externally accessible is trimpot VR4, so it's a good idea to figure out what you want to do with this before you close the case. But note that the *Pedal* is designed so that you can drill a hole in the base to externally adjust VR4 with a screwdriver.

We prefer to leave VR4 fully clockwise so that there is a substantial limiting action when in boost. But you might want to adjust VR4 so that the second distortion stage has a similar effect to the first, and they combine more evenly with the distortion control adjustments. It is a matter of personal preference.

Many amplifiers for musical instruments have an earth loop switch which allows the common shield connection of the jack lead to either be earthed or floating. When used with a guitar that has piezo pickups, you should get less hum when it is connected to earth.

Oscilloscope screen grabs Scope1-Scope8 show how the output waveform varies with a range of different control settings. See those screen grabs for more details.

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Gear to help you brew that perfect beer...
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PROGRAMMABLE THERMAL REGULATOR

by Tim Blythman and Nicholas Vinen

Precision temperature control is an integral part of many industrial processes. If you are interested in making your own brewed or fermented foods as a hobbyist, you will find that it's important to accurately maintain the temperature of the process to get the best results.

From time to time, we have tried to make our own cheese, beer and cider (not at the office, of course!).

For beer, malted barley is fermented by yeast to create alcohol and develop flavours. The fermenting activity also adds effervescence to the finished product. The fermentation (say, for home-brew beer or cider) takes place in a food-grade plastic container. Good results *may* be achieved by merely keeping the vessel in a room where the temperature does not vary much, perhaps wrapping it with a blanket in the cooler months.

But for consistency and to ensure that fermentation completes correctly (if it doesn't, that's when bottles start to explode!), you need a way to monitor and control the brew temperature. Proper temperature regulation is one reason that commercial breweries can ensure that each batch of beer tastes the same as the others.

Even keeping the brew vessel in a thermostatically controlled room may not be sufficient. As the fermentation progresses, the yeast activity rises and falls. The heat generated varies, which can alter the temperature of the brew from the inside, even if the outside temperature is steady. Thus we need a means of both measuring and changing the temperature of the brew.

We have chosen Peltier devices for this because they have the ability to both heat *and* cool; they only require a low-voltage DC supply, and they are easy to control. They are not the most efficient devices, but are adequate for small scale operations.

Sous-vide cookery

Another application for our *Thermal Regulator* is sous-vide cookery. While the term French *sous-vide* literally translates to 'under vacuum', the vacuum is not critical. The success of sous-vide cookery is mostly due to precise temperature control.

We'll go into a bit more detail about this later, but the important thing is that a tightly controlled temperature leads to consistent and repeatable results.

By keeping the food hot enough for long enough, you ensure that any bacteria is killed, and thus it is safe to eat.

Other areas of cookery which work well with precise temperatures include the tempering of chocolate. Taking the chocolate along a well-defined temperature profile alters its structure and produces a glossy appearance and crisp texture when the chocolate hardens.

One of the intriguing possibilities with this device is that you could use it to keep food at a safe storage temperature (around 4°C, like the inside of a refrigerator) for many hours and then at a preset time, heat it up and cook it, so it is ready for you to eat.

If doing this, we suggest you modify the software to trigger an alert if the food temperature went significantly above 4°C in storage mode, so you know that it is safe to eat.

And more

Many people who have worked in a laboratory will be familiar with the laboratory water bath as a way of keeping test samples at a fixed temperature. Naturally, the *Thermal Regulator* is well suited to this application too.

We've even joked about using the *Thermal Regulator* as a personal air-conditioner. Joking aside, the radiator does produce a refreshing breeze when it's set to heat, so we reckon it actually would do that job pretty well.

Thermal Regulator electronics

The *Thermal Regulator* electronics consists of three main parts. An Arduino Uno board (or compatible) provides a microcontroller as well as some power regulator circuitry.

A Peltier Driver shield (Arduino add-on board) implements a high-power full H-bridge which is controlled by the Arduino. This is used to drive the Peltier devices.

A second shield (the Interface shield) has numerous inputs and outputs; it is primarily concerned with sensing what is happening with the Peltier devices and can also drive other devices such as pumps and fans.

We'll expand on these later. You will need to be familiar with the Arduino IDE to construct this project; it can be downloaded for free from: **www.arduino.cc/en/software**

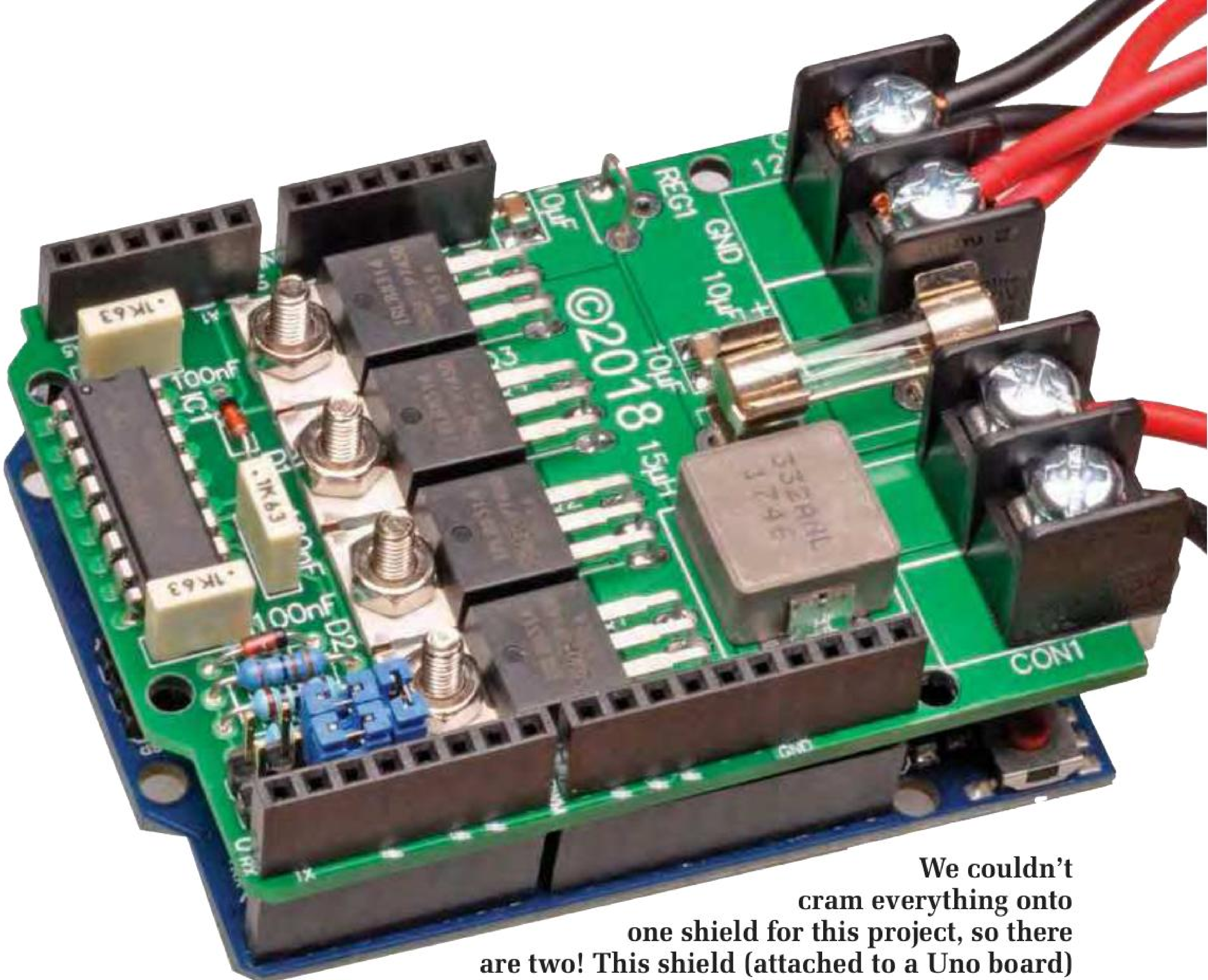
As this circuitry has so many potential uses, we've designed the control circuit to be as flexible as possible. Before continuing, you may wish to read the accompanying panel, which describes how Peltier devices work.

The inspiration for this article

Thinking about drinks cooler projects gave us the idea for this series of articles. Coolers can involve quite a large heatsink and fan attached to a single Peltier module to try to get all the waste heat out and keep the Peltier running efficiently. If you use several Peltier devices to try to pump more heat, you end up needing a huge heatsink. While simple and relatively cheap, this is not an ideal solution.

Consider, for example, that a car engine puts out a vast amount of heat (hundreds of kilowatts in some cases). While early engines were air-cooled, most manufacturers quickly moved to liquid cooling. It is much easier to remove all that heat with a bit of water flow, which can then go to a large radiator with sufficient surface area to transfer that heat to the air.

So we thought, why not apply the same principles to Peltier devices? Small radiators, such those used in water-cooled computers are now readily available at modest cost, and the required fans, pumps and tubing do not cost much either. We then bought some parts and performed a series of experiments which brought us to develop what we are presenting in this design.



We couldn't cram everything onto one shield for this project, so there are two! This shield (attached to a Uno board) is designed to drive Peltier devices at up to 20A in bridge mode, meaning the current can be reversed and the Peltier can be used to perform heating or cooling. There's a number of surface-mounted devices on this shield, but none of them are too small, so construction is not difficult.

One example

Sous-vide cookery is a good example to demonstrate what our resulting hardware can achieve.

As we mentioned, the term 'sous-vide' translates to 'under vacuum'. This term has little to do with the process except that the items to be cooked (typically meat, fish or eggs) are usually vacuum-sealed into a waterproof bag before being immersed in a temperature-controlled water bath.

A cheap alternative is to use a 'snap-lock' type sandwich bag. Careful sealing of the bag can ensure that most of the air is removed before sealing.

The bag has the effect of keeping the water separate from the food so that it does not dilute any flavours. The removal of air by the vacuum process also means that there are no air bubbles which might cause the bag to float to the surface and not be fully immersed. The aim then is to use the water bath to achieve a precise food temperature. For example, a piece of beef cooked medium rare should have a core temperature of 60°C.

Immersion in the water bath is a good way to accurately and consistently hit this target.

Thus our *Thermal Regulator* needs to be able to reach and maintain a steady temperature in a water bath to be useful in this application; ideally, it should be capable of heating to well over 60°C (we hit 75°C+ in testing).

One of the interesting things about sous-vide cooking is that you can cook at much lower temperatures than you might expect, as long as you maintain that temperature for long enough. This creates textures and flavours that are very different from what you get with regular boiling, baking or frying.

There's a lot more to sous-vide cookery than this; we simply want to explain why you might need such a thing as a precisely controlled water bath.

There are many guides to the sous-vide process, and you should do further research before trying this technique.

We also mentioned that brewing and fermenting could be enhanced by implementing accurate temperature controls. In this case, your brewing or fermenting vessel can be placed

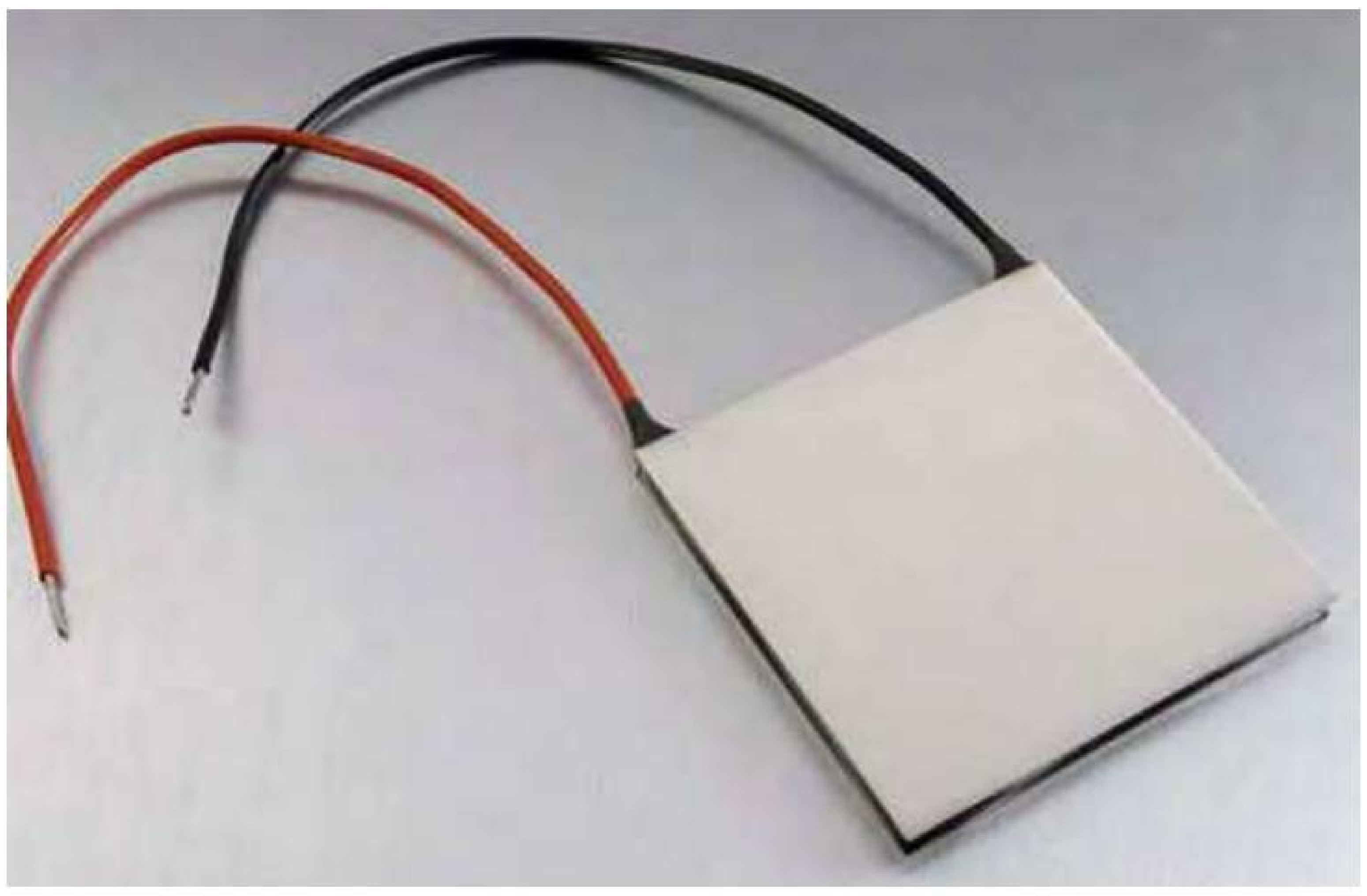
Features

- Active cooling and heating
- Controls 200W+ of Peltier devices
- Utilises multiple temperature sensors
- Arduino-based for flexibility

Possible uses

- Cheesemaking
- Beer/wine/cider/kombucha brewing
- Tempering chocolate
- Sous-vide cooking
- Computer cooling
- Laboratory water bath
- Aquariums (especially large tropical)
- Personal air-conditioner
- Improved cooling for laser cutters

How Peltier devices work



A Peltier device is effectively an electric heat pump with no moving parts. An electric current through the device causes heat to move from one side to the other. It consists of one or multiple junctions of dissimilar metals, across which a voltage is applied. The general construction of such a device is shown in the accompanying figure.

The laws of thermodynamics do not allow heat or coldness to be 'created'; these are merely a consequence of energy being moved from one place to another. For example, electric heaters convert electrical energy to heat energy in a 1:1 ratio. Unfortunately, the law of entropy means that we must expend energy to move this heat energy around. Hence the process cannot be 100% efficient.

The reverse of the Peltier effect is called the Seebeck effect, where a temperature difference is converted into a voltage. The energy delivered by that voltage comes from the thermal energy flowing from the hot side to the cold side. This is the effect used by temperature-sensing thermocouples and thermopiles.

The Seebeck effect can also be observed in Peltier devices, although they are not designed with this in mind and so are not very efficient. For example, if power is applied to a Peltier device for a few seconds (enough to cause a temperature difference) and then removed, a voltage can be measured at the device's terminals. This is due to the Seebeck effect of electricity generated from the residual temperature difference.

A Peltier device consists of an array of alternating materials, resulting in alternating junctions with opposing behaviours. They are arranged so that heat is transferred from one side to the other, by keeping each type of junction on its own side.

You may well be familiar with Peltier devices in small drinks chillers – 'miniature fridges' used to help get drink cans cold. What you might not realise is that these fridges can (in theory) also be used as heaters because one upside of the Peltier effect is that it is reversible. If the direction of the current is reversed, then the heat flows in the opposite direction.

If you have used this type of cooler then you'll know they do a fair job, but most are no competition for a regular household refrigerator or air-conditioner, which use a compressor and do not suffer from the side-effects noted below.

While Peltiers have the benefit of reversibility and no moving parts, they do have their downsides. In particular, the materials which provide the strongest Peltier effect are not good thermal insulators; in effect, the heat can leak from the hot side back to the cold side. This effect becomes stronger as a higher temperature difference is generated across the device.

Practical Peltier devices are typically made of semiconductor materials with a finite resistance. As such, they are also subject to resistive heating due to the current flowing through them. This is calculated as I^2R, so a doubling of current will result in four times as much dissipation. But the amount of heat that is pumped is proportional to the current, so Peltier devices work best when demands on them are modest.

Peltier devices are typically made out of brittle ceramics. These are necessary to provide electrical insulation while allowing heat to be effectively conducted to the working surfaces.

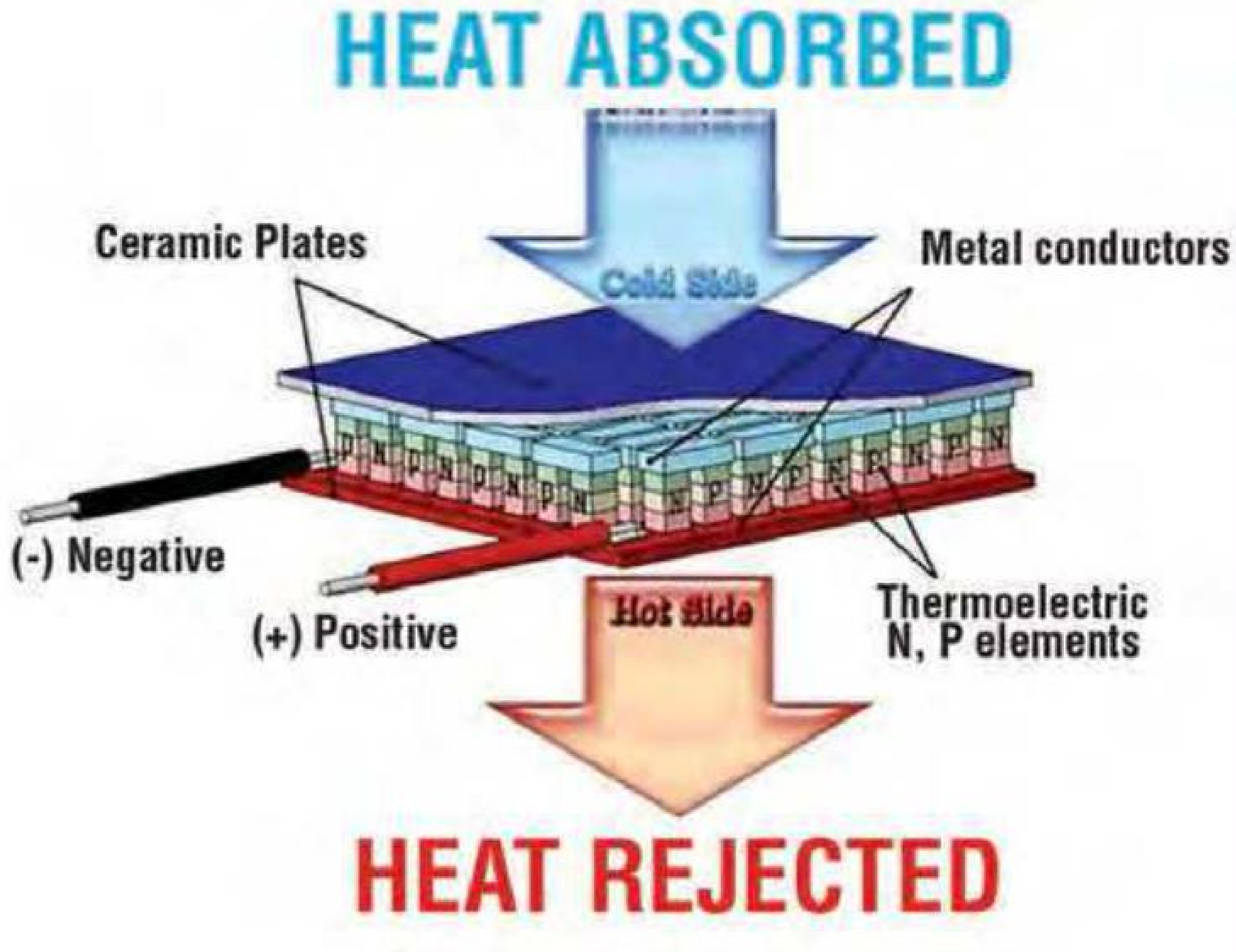
Safely driving a Peltier

Rapid changes in current can cause a temperature gradient; the resulting temperature changes can create thermal stress and even cracking. Using techniques like PWM (pulse-width modulation) to modulate the current must be done carefully to avoid damage. At the very least, the PWM frequency should be high enough to sidestep these effects.

Many Peltier device manufacturers specify that low ripple power (of the order 5-10%) should be supplied to the devices. For optimal results, a pure DC voltage should be applied.

There is another reason to avoid PWM. Consider the case of pure 6V DC being applied to a Peltier device compared to 12V DC at a 50% duty cycle. When we look at the I^2R losses, we can see that these are doubled in the 12V case. Although the 50% duty cycle means power is applied half the time, double the voltage means that the I^2R effect is quadrupled.

Our Peltier Driver shield has been designed with these factors in mind. It delivers nearly pure variable DC across the full range of positive and negative voltages, allowing both heating and cooling. This also has the effect of making the power source's life a lot easier!



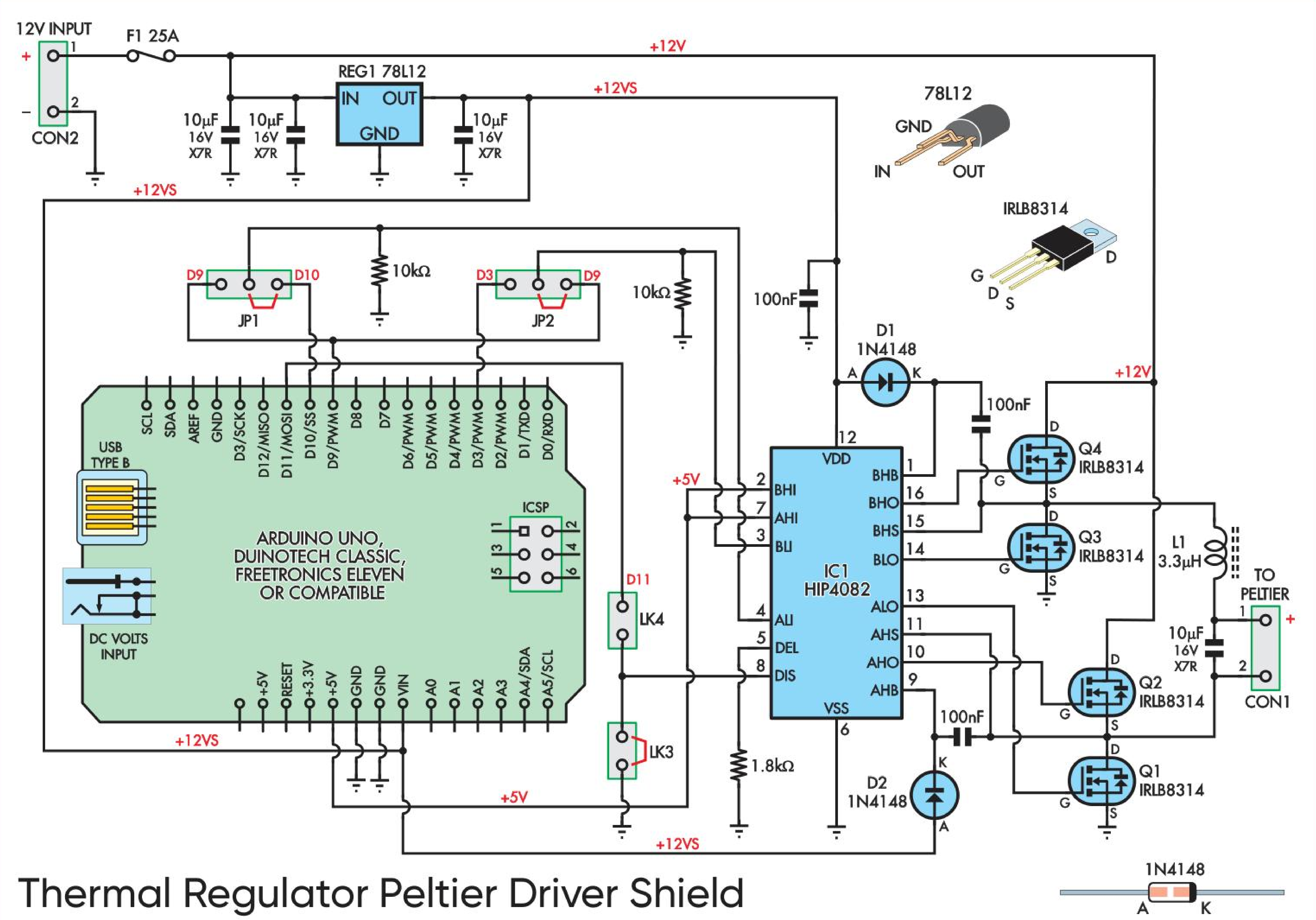
A Peltier device is usually made from an array of semiconductors which are electrically connected in series, but thermally in parallel due to the way the interconnectors are arranged. This way, when a voltage is applied, heats flows from one side to the other, depending on the voltage polarity. (Image source: http://bit.ly/pe-mar21-peltier**)**

inside the water bath, such that the temperature-controlled water practically surrounds it.

Having the bath itself being inside a well-insulated container (we used a small foam cooler for our experiments) reduces the demands on the Peltier devices and it has the further advantage of minimising external effects such as drafts.

The Peltier Driver shield

Fig.1 shows the circuit of the Peltier Driver shield. As mentioned earlier, it is based on a high-power H-bridge. DC power is fed in via terminal block


12V INPUT
F1 25A
+12V
CON2
REG1 78L12
IN
OUT
GND
10µF 16V X7R
+12VS
78L12
GND
IN
OUT
IRLB8314
G
D
S
10kΩ
D9
D10
D3
JP1
JP2
100nF
D1 1N4148
A
K
+12V
USB TYPE B
SCL
SDA
AREF
GND
D13/SCK
D12/MISO
D11/MOSI
D10/SS
D9/PWM
D8
D7
D6/PWM
D5/PWM
D4/PWM
D3/PWM
D2/PWM
D1/TXD
D0/RXD
ICSP
ARDUINO UNO, DUINOTECH CLASSIC, FREETRONICS ELEVEN OR COMPATIBLE
DC VOLTS INPUT
+5V
RESET
+3.3V
VIN
A0
A1
A2
A3
A4/SDA
A5/SCL
D11
LK4
LK3
+5V
12
VDD
BHI
AHI
BLI
ALI
DEL
DIS
VSS
BHB
BHO
BHS
BLO
ALO
AHS
AHO
AHB
IC1 HIP4082
Q4 IRLB8314
Q3 IRLB8314
Q2 IRLB8314
Q1 IRLB8314
L1 3.3µH
TO PELTIER
CON1
1.8kΩ
D2 1N4148
1N4148

Thermal Regulator Peltier Driver Shield

Fig.1: the Peltier Driver shield has four MOSFETs in an H-bridge configuration (Q1-Q4), an LC filter to smooth the voltage across the Peltier devices and one HIP4082 bridge driver (IC1). Its control pins can go to different Arduino pins depending on the settings of links LK1-LK4.

CON2 and fuse F1, then to optional 12V regulator REG1.

REG1 is only needed if the supply voltage is above 15V, as many Arduino boards cannot sustain more than 15V at their VIN pin.

Otherwise, REG1 can be linked out or omitted entirely if 12V is available from one of the other attached boards. The regulated 12V power (from whichever source) is also fed to the VDD pin (pin 12) of IC1, an H-bridge MOSFET driver IC. It also has a maximum VDD of 15V, although it can control a bridge which handles up to 80V.

IC1 has its control inputs fed from jumper links LK1-LK4. These allow IC1's input pins to be connected in different combinations to various PWM-capable pins on an Uno board. Two 10kΩ pull-down resistors ensure that the pins are in safe states (with the H-bridge shut down) when the Uno is in reset or not programmed.

The 1.8kΩ resistor connected to IC1's DEL pin (pin 5) sets the turn-on delay and thus the dead-time of the MOSFETs to around 200ns.

Diodes D1 and D2, and their associated 100nF capacitors form the 'bootstrap' circuits which provide high enough voltages to drive the gates of high-side MOSFETs Q2 and Q4, using the output square waves to form a charge pump.

IC1 also has its own 100nF supply bypass capacitor.

MOSFETs Q1-Q4 are four IRLB8314 N-channel types, arranged in an H-bridge configuration. These can switch 30V at over 100A with sufficient cooling, although the current is limited by other parts of the circuit, such as PCB tracks and connectors.

Using an H-bridge means that the direction of current flow can be reversed, and the duty cycle can also be controlled by rapidly switching the H-bridge between two states.

The driver (IC1) is needed because the high-side MOSFETs are N-channel varieties. Thus their gates need to be taken above their source pins, ie, above the supply rail; the bootstrap circuit provides the means to do this. The driver also ensures that the MOSFET gate capacitances can be charged and discharged rapidly to provide a high PWM frequency so that we can filter it to get a smooth voltage across the Peltiers.

The MOSFETs' low on-resistance of around 2.4mΩ means that minimal heatsinking is required; at modest currents (up to about 20A), the PCB itself provides sufficient heatsinking.

Between the output of the H-bridge and the output connector (CON1) is an LC low-pass filter comprising a 3.3µH inductor L1 and a 10µF multi-layer ceramic capacitor. This arrangement forms a sort of crude 'buck' DC/DC step-down converter.

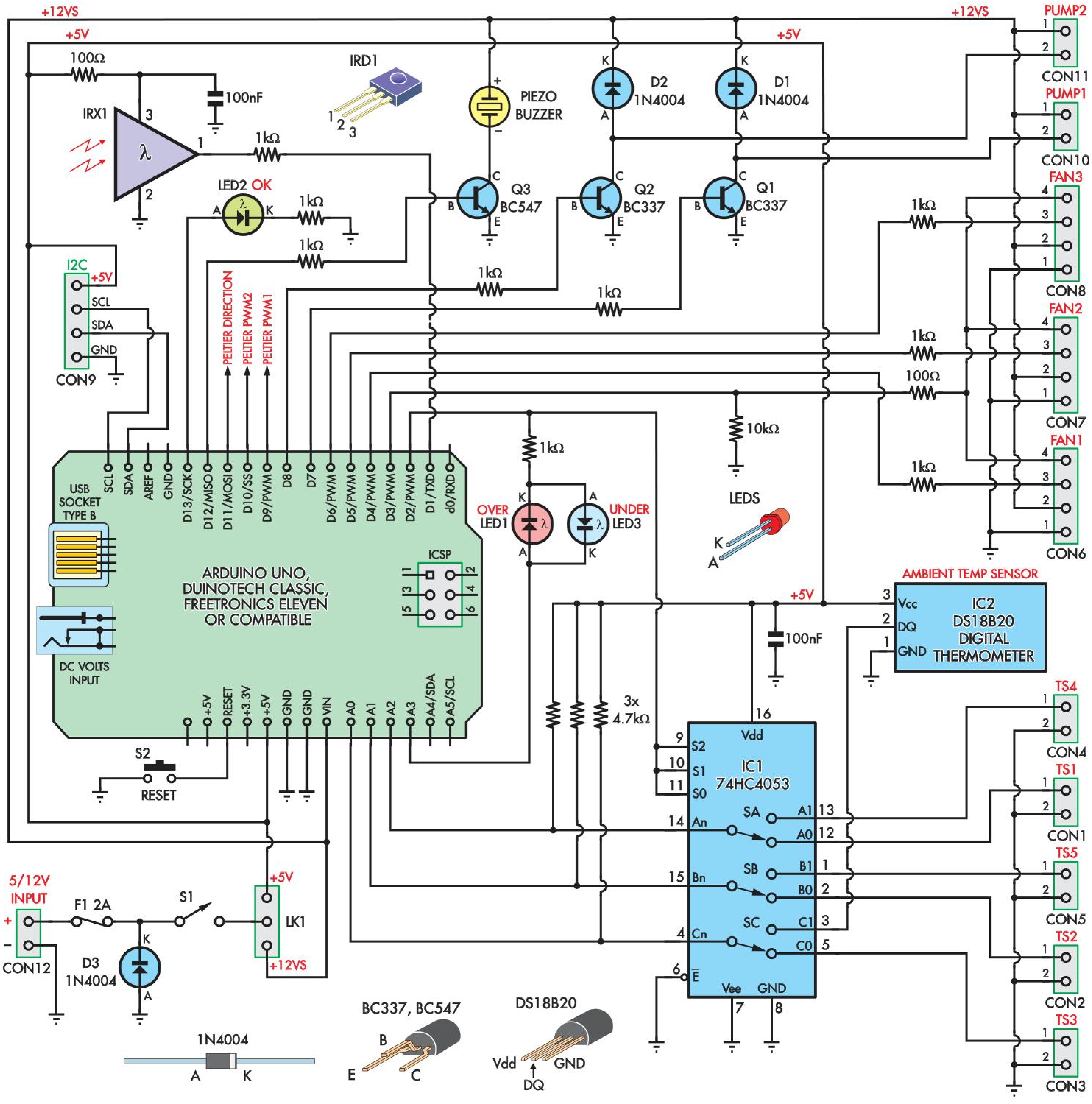
When a high enough frequency PWM signal is applied to the control inputs of IC1 (around 300kHz), the output is effectively DC. This also means that the current drawn from the nominally 12V rail is effectively DC, so no bulky bypass capacitors are required on the board.

One way of analysing this circuit is to assume that the Peltier devices have an effective resistance of around 1Ω (12A @ 12V).

We can then calculate that the 300kHz PWM signal is attenuated by a factor of 100 (around 40dB) and so the ripple is kept well below the recommended 5%.

This shield is suitable in any case where variable, relatively smooth high-current unregulated DC power is required.

The part chosen for L1 in our prototype has an 19A rating, but even if


+12VS
+5V
100Ω
100nF
IRX1
λ
IRD1
PIEZO BUZZER
D2 1N4004
D1 1N4004
K
A
1kΩ
LED2 OK
Q3 BC547
Q2 BC337
Q1 BC337
B
C
E
I2C
+5V
SCL
SDA
GND
CON9
PELTIER DIRECTION
PELTIER PWM2
PELTIER PWM1
PUMP2
CON11
PUMP1
CON10
FAN3
CON8
FAN2
CON7
FAN1
CON6
10kΩ
LEDS
USB SOCKET TYPE B
DC VOLTS INPUT
SCL SDA AREF GND D13/SCK D12/MISO D11/MOSI D10/SS D9/PWM D8 D7 D6/PWM D5/PWM D4/PWM D3/PWM D2/PWM D1/TXD d0/RXD
ARDUINO UNO, DUINOTECH CLASSIC, FREETRONICS ELEVEN OR COMPATIBLE
ICSP
+5V RESET +3.3V +5V GND GND VIN A0 A1 A2 A3 A4/SDA A5/SCL
OVER LED1
UNDER LED3
AMBIENT TEMP SENSOR
IC2 DS18B20 DIGITAL THERMOMETER
Vcc DQ GND
3x 4.7kΩ
IC1 74HC4053
Vdd S2 S1 S0 An Bn Cn SA SB SC A1 A0 B1 B0 C1 C0 Ē Vee GND
TS4 CON4
TS1 CON1
TS5 CON5
TS2 CON2
TS3 CON3
S2 RESET
5/12V INPUT
CON12
F1 2A
S1
D3 1N4004
LK1
+12VS
1N4004
BC337, BC547
DS18B20
Vdd DQ GND

Thermal Regulator Interface Shield

Fig.2: the Interface shield monitors up to five thermistors, and it can drive several auxiliary 12V devices which may be required, including fans and pumps. Multiplexer IC1 allows through analogue inputs to sense six temperature sensors, as some analogue inputs are reserved for I^{2}C serial communications.

this is upgraded, the PCB traces and connectors max out at around 20A. The MOSFETs limit the supply voltage to 30V.

Interface shield

The Interface shield (circuit shown in Fig.2) connects to up to six temperature sensors, can drive up to three PWM-capable fans and two small pumps.

One of the temperature sensors is a DS18B20 fitted to the PCB to sense ambient temperature; the remaining five channels suit either DS18B20 digital sensors or low-cost NTC thermistors (via CON1-CON5).

The shield also provides three status LEDs (red, green and blue), a buzzer and an infrared receiver for user input.

Four-way header CON9 breaks out the Arduino's I^{2}C peripheral. Though this suits many sensors and modules, our primary intent is to drive a character LCD module, similar to those we described in the June 2018 issue. This sort of display is easy to drive and well suited to showing a large number of changing parameters, such as temperatures and fan speeds, in near real-time.

No I^{2}C pull-ups are provided on the board, as these are fitted on the LCD interface module.

CON12 allows power at 5V or 12V (set by JP1) to be fed into the shield. D3 provides reverse polarity protection by conducting enough current to blow fuse F1 if the supply is reversed. Switch S1 can be used to switch this supply on or off.

If JP1 is set to the 12V position, power is fed to the Uno's VIN pin, which in turn provides regulated 5V back to the shield via the Uno's 5V regulator and pin. The 5V position feeds power directly to the 5V pin.

The jumper can also be left off, if, for example, 12V (VIN) and 5V rails are available from elsewhere;

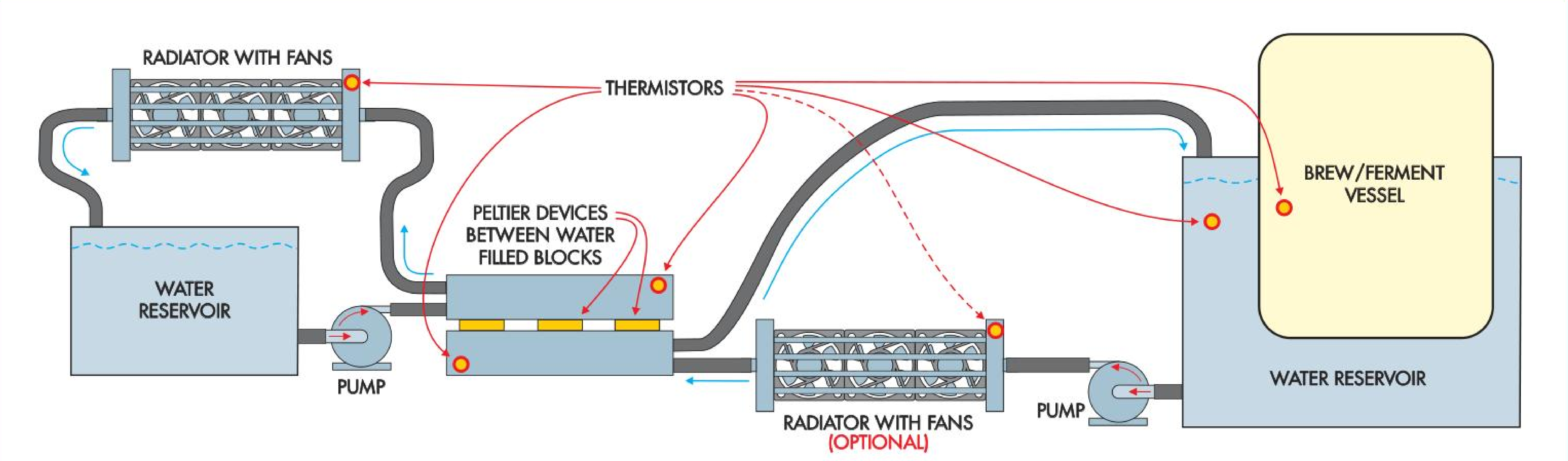


Fig.3: this ‘circuit’ shows how the *Thermal Regulator* could be used to control a sous-vide cooker or for making cheese or fermenting beer or wine. While the two loops make the hardware a bit more complex, this makes it capable of moving more heat around, necessary to achieve the higher temperatures needed for cooking.

for example from an attached Peltier Driver shield.

Although the Uno has six ADC channels (analogue inputs), two of these pins are shared with the I^{2}C peripheral and so cannot be used. Thus IC1, a 74HC4053 triple two-way analogue multiplexer, is used to switch the A0, A1 and A2 analogue input pins between CON2, CON3 and CON1 respectively in one state, and IC2 (the DS18B20), CON4 and CON5 respectively in the other state.

The control inputs for all three multiplexer channels are connected together, to digital pin D2 on the Uno. The output-enable ($\overline{E}$) pin is connected to ground, so the three switches in IC1 are always active.

The A0, A1 and A2 pins have separate 4.7kΩ pull-up resistors to the 5V rail, which provides parasitic power if a DS18B20 is fitted or forms the top half of a voltage divider circuit if an NTC thermistor is fitted.

CON6, CON7 and CON8 are four-way plugs for the connection of PWM-capable fans. Their 12V and GND supplies are taken from the VIN pin and GND pin of the shield.

The tachometer outputs are fed to Arduino pins D4, D5 and D6 respectively via 1kΩ resistors. These can be set as digital inputs to sense the fan speeds.

A common PWM signal to the fans is provided from Arduino pin D3 via a 100Ω resistor. This line also has a 10kΩ pull-down, so the fans are off during reset.

CON10 and CON11 are for the control of small 12V pumps. Each is switched by a low-side NPN transistor (Q1 and Q2), controlled by Uno pins D7 and D8 via 1kΩ resistors.

Snubbing diodes D1 and D2 are connected directly across the outputs at CON10 and CON11. They absorb any back-EMF spikes when the pumps switch off.

Similarly, piezo buzzer PB1 is controlled by NPN transistor Q3. Its base is driven from Arduino pin D12 via a 1kΩ current-limiting resistor.

Of the three onboard LEDs, LED2 is driven directly by pin D13 going high and sourcing current through a 1kΩ resistor. LED1 and LED3 are connected in anti-parallel between pins D2 and A3 with a 1kΩ series resistor. LED1 lights when A3 is high and D2 is low; LED3 lights when D2 is high and A3 is low.

Naturally, both cannot be on at the same time. This arrangement means that the LEDs may flicker when D2 is being switched to scan the temperature sensors, but this only happens briefly.

Infrared receiver IRX1 is powered via a 100Ω resistor and bypassed by a 100nF capacitor. Its output is fed to Arduino pin D1 via a 1kΩ resistor. The UART peripheral also uses D1, so it cannot be used at the same time as the receiver.

Pins D9, D10 and D11 are left free and are intended to be used to control the Peltier Driver shield.

We have written several functions and routines to control the Interface shield, including such things as thermistor calibration curves and interrupt-based tachometer speed signal processing.

A minor limitation of the code as written is that it only supports the single DS18B20 fitted to the PCB. It’s possible to read the temperature from other DS18B20s running on parasitic power from CON1-CON5 by altering the code, but this will considerably slow down temperature sampling.

We did this because we found the performance of the cheap NTC thermistors to be adequate.

Power

Anything to do with moving significant amounts of heat around requires a fair amount of power. We used four 5A Peltier devices in our prototype. The fans, pumps and shield add up to no more than an amp.

Most Peltier devices are rated to run at up to 15V. Thus we need around 21A at approximately 15V. The reduced I^2R losses are a good reason to use a slightly lower voltage like 12V, which is also more common.

For our prototype, we used an ATX computer power supply capable of delivering 22A from its 12V rail.

While this sounds quite close for comfort, the supply’s other output rails (eg, 5V or 3.3V) have practically no demand. We found the power supply stayed comfortably within specification overall, and the power supply did not show any signs of stress under continuous operation.

Alternatives include a 15V or 13.8V open-frame power supply module or a high-current bench power supply.

We even did some initial testing using our 45V/8A supply from October-December 2020, although this is a poor use of its talents!

We’ll show how we rigged up the ATX power supply; other supply options will probably be quite simple in comparison.

Other hardware

As you might imagine, there’s a bit more to this project than the electronics. Fortunately, most of the parts are readily available at online sites such as AliExpress and eBay.

Before construction, we recommend you thoroughly read about our designs to see what you need, as there is a fair bit of flexibility possible.

As mentioned above, our main heat transfer medium is water. It has a superb heat capacity (it can hold a lot of thermal energy for a given mass) and it has fair thermal conductivity (it’s easy to move heat energy in or out of water). Plus, there is a lot of off-the-shelf equipment suitable for working with water.

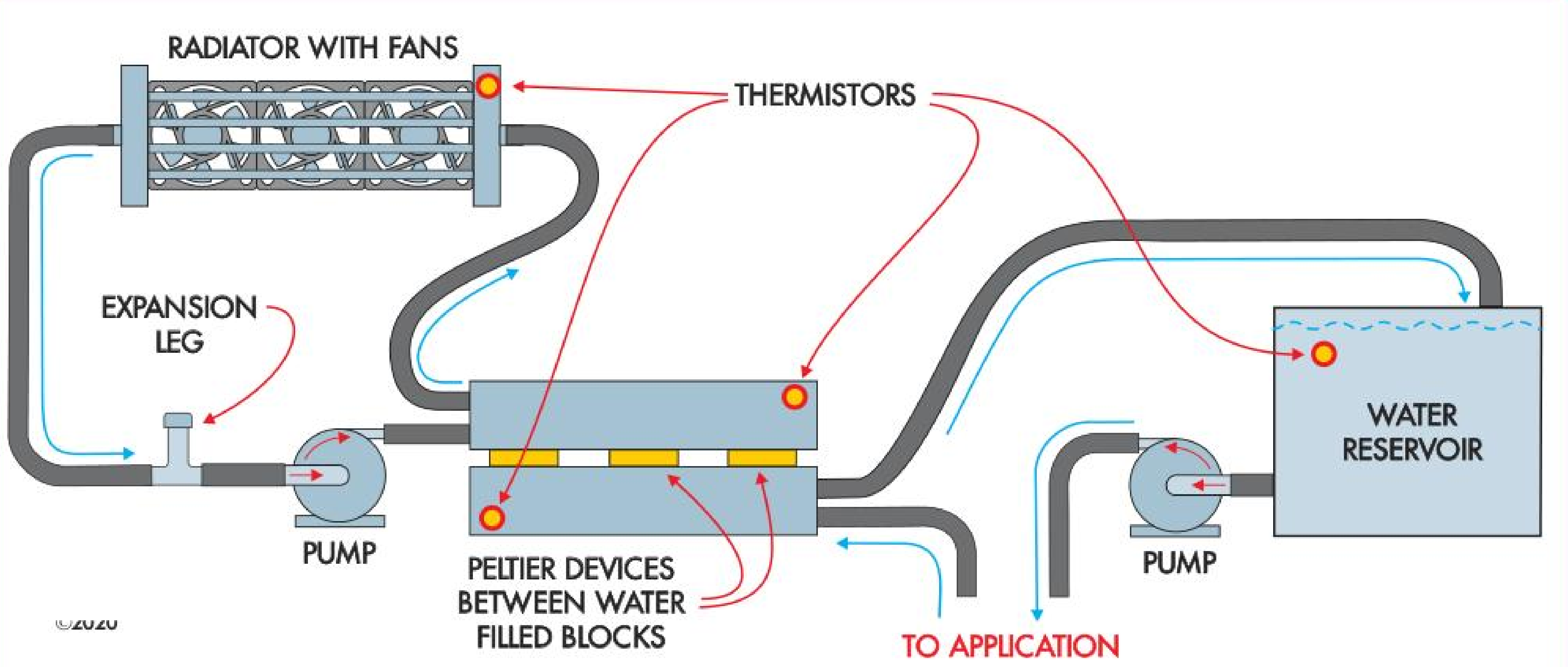


Fig.4: this is a variant of Fig.3. The vessel on the left-hand loop has been replaced by an expansion leg, the opening of which should be the highest part of the loop to avoid spillage. You can use the water from the right-hand loop to cool or heat whatever you need (such as a personal air-conditioner made from another radiator and some fans).

For example, the pumps we are using are similar to what might be used to circulate water in an aquarium.

Naturally, you should take care that there is no chance of water getting in the electronics (or vice versa).

The thermal loop

We manage the temperature of the water bath by circulating water through one or more loops. The movement works to keep the water mixed so that there are no hot and cold spots. Fig.3-Fig.6 show some variations on the water 'circuits' that are possible with our hardware.

Fig.3 shows the set-up that you might use for fermentation, while Fig.4 shows a general heating/cooling application and Fig.5 shows a simplified fermentation application (which would be cheaper to build but possibly less effective).

Fig.6 shows how we used the *Thermal Regulator* to pre-cool the water for our laser cutter, reducing the laser's operating temperature on hot days (more on that later).

You may realise from these diagrams that the water loop(s) mean that we can keep the radiators/heatsinks/fans which dump the 'waste heat' into the air well away from what we are trying to regulate.

This is a key benefit to using water to transfer heat. Using a larger volume of water means that the setup will be more robust to external changes, but will take longer to reach its target setpoint. The aim here is to move the heat to or from where we want it as effectively as possible. The loops allow the heat to be moved easily.

The parts required

Many of the parts we used were obtained as part of a kit. These kits are typically sold for water cooling computers (eg, for overclocking). We also had to get a few other miscellaneous bits and pieces.

The water is moved by small 12V submersible pumps. These are cheap and draw around 300mA each. The water is not being pumped to any great height, as it is generally around a closed circuit, so a high pressure or 'head' is not needed. Generally, as long as the water is moving to some degree, we can maintain the level of heat transport we need.

To join everything together, we used flexible silicone tubing. We obtained this as part of our kit, although you can also get it from hardware or camping stores. We found that the most useful size has an inside diameter of approximately 8mm and is a good friction fit to the barbed fittings on the other parts.

Although the tube is a tight fit, we didn't trust this completely. To secure the tubing, we used small (6mm-16mm) hose clamps.

Where we needed to bend the tube at a sharp angle, we used small barbed brass elbows and T-pieces. These too should be secured in place with hose clamps.

The final part of our primary circuit is the water block. This consists of a block of aluminium with two barbed fittings at one end. It provides a good thermal interface between the water and the Peltier devices, allowing heat to be readily transferred.

The water enters at one end, passes up and back along the block and back out the other fitting. Aluminium is a pretty good thermal conductor, and it is cheap and easy to work with.

In a typical application, the Peltier devices are clamped to a flat surface of the water block with thermal compound in between, forming a tight fit over a large area that conducts heat well.

Naturally, the Peltier devices have two sides, and whatever heat is removed from one side needs to be dealt with on the other side. The simplest method is to use a heatsink block which is actively cooled by fans.

In our 45V 8A PSU design (see earlier), we used a pair of high-powered fans on a heatsink and found this to be capable of dispersing a few hundred watts.

We ran some trials using this technique with Peltiers and it fared well, but not as well as a proper radiator.

The better technique uses a second water loop to remove heat from the other side of the Peltier device.

This uses a second pump and associated piping similar to the water bath. The water from the second loop goes through a fan-cooled radiator.

The radiator is like a smaller version of the radiator in a car. Water passes through the radiator and air is moved over it by the fans.

If the water is warmer than the air, then the water is cooled (and the air is warmed). If the water is cooler than the air, then the water is warmed.

The radiator works better because it has a larger area for transporting heat and moves more air, but it is also a more complex arrangement.

This is the arrangement we have fitted to our laser cutter.

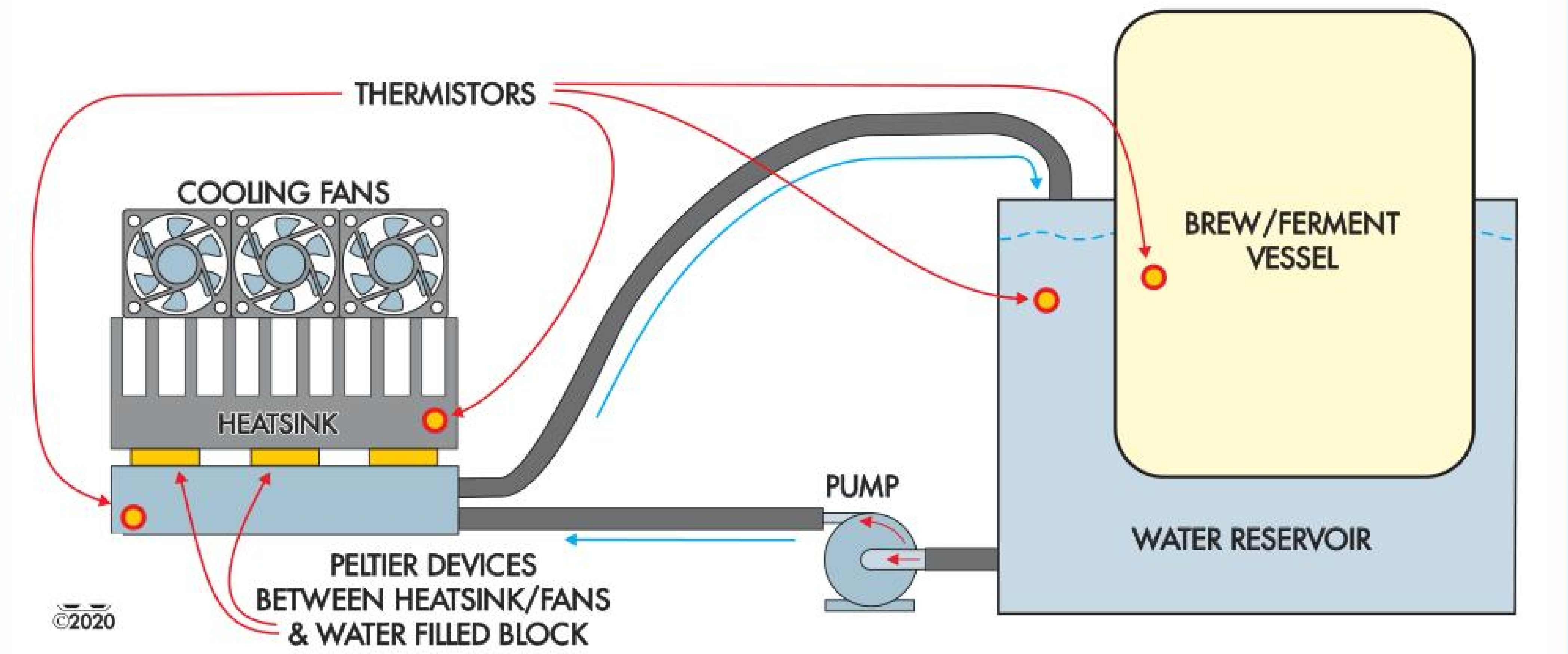


Fig.5: the minimal viable hydraulic circuit. For simplicity, we use a fan-heatsink combination instead of a second water loop. While not quite as effective as a radiator, this sort of configuration can move a few hundred watts of heat.

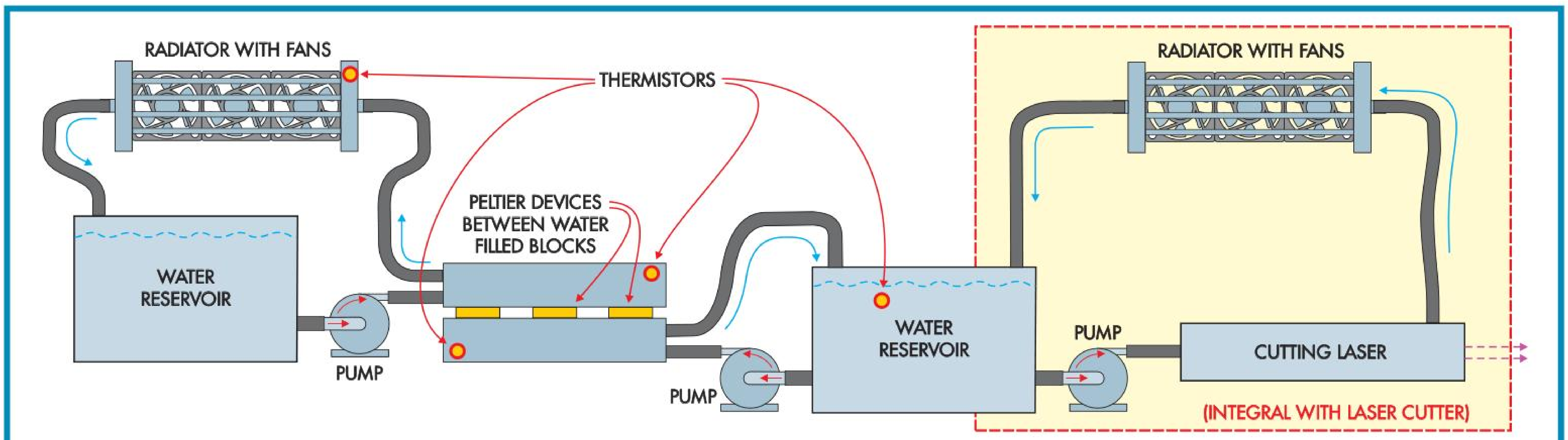


Fig.6: this is the arrangement that we have installed onto our laser cutter, to help 'boost' the laser cooling on hot days. It reduces the laser temperature by around 6°C compared to purely passive cooling (which is pretty good when you consider that with passive cooling, it operates at 10°C above ambient).

In the photos, you can see the various thermistors used throughout the rig. We can tell a lot about how the system is performing by the temperature readings. In particular, the temperatures at the hot and cold sides of the Peltier devices indicate how hard they are working and indicates the best strategy is for extracting the best thermal performance.

We will explain more later, but at times it is beneficial to switch off power to the Peltier devices. And of course, we use other sensors to measure the temperature at our water bath to be able to reach the target temperature – and know when we have done so.

Water vessel for brewing ...

Another part that is not included in typical computer water-cooling kits is the reservoir for the water. The choice (size) of this will of course depend on your application.

Brushless DC Pump
AD20P-1230C
Input: DC 12V 3.6W IP68
Hmax: 300 cm
Qmax: 240 L/H
Giant Electric Tech Inc

These pumps are small and only draw around 300mA. They are sealed and thus fully immersible (the impeller is coupled to the shaft by magnets). Since they are not raising the water to any great height, not much power is needed. The main thing to ensure is that the intake is always fully submerged, as they are not self-priming.

While you might be tempted to think that, for the fermentation application, you could circulate the fermenting liquid directly past the Peltiers, we strongly recommend against this. We could see no assurances anywhere that the parts we used were food safe and in any case, any beer left behind in the fluid circuits would be very difficult to clean out.

Beer is slightly acidic, and many cleaning solutions are strongly alkaline. The fittings may not be able to withstand these sort of chemicals.

Thus, for brewing and fermenting applications, we suggest using a large water bath in which the brew vessel is placed. Assuming that you are using one of the plastic 25L units, a plastic storage container like those available from discount variety stores and hardware stores is the simplest option.

The larger container behaves as a water jacket. It does not need to enclose the smaller brew vessel completely, but should come most of the way up the sides of it to improve the surface area over which heat is transferred. A hole cut in the larger vessel's lid (forming a seal of sorts around the brew vessel) will reduce the amount of evaporation that might occur and thus reduce the power needed to maintain temperature.

Such a large vessel can lose (or gain) heat from the surroundings due to its large surface area, so a modest amount of insulation may help; something as simple as a towel may suffice.

... and cooking

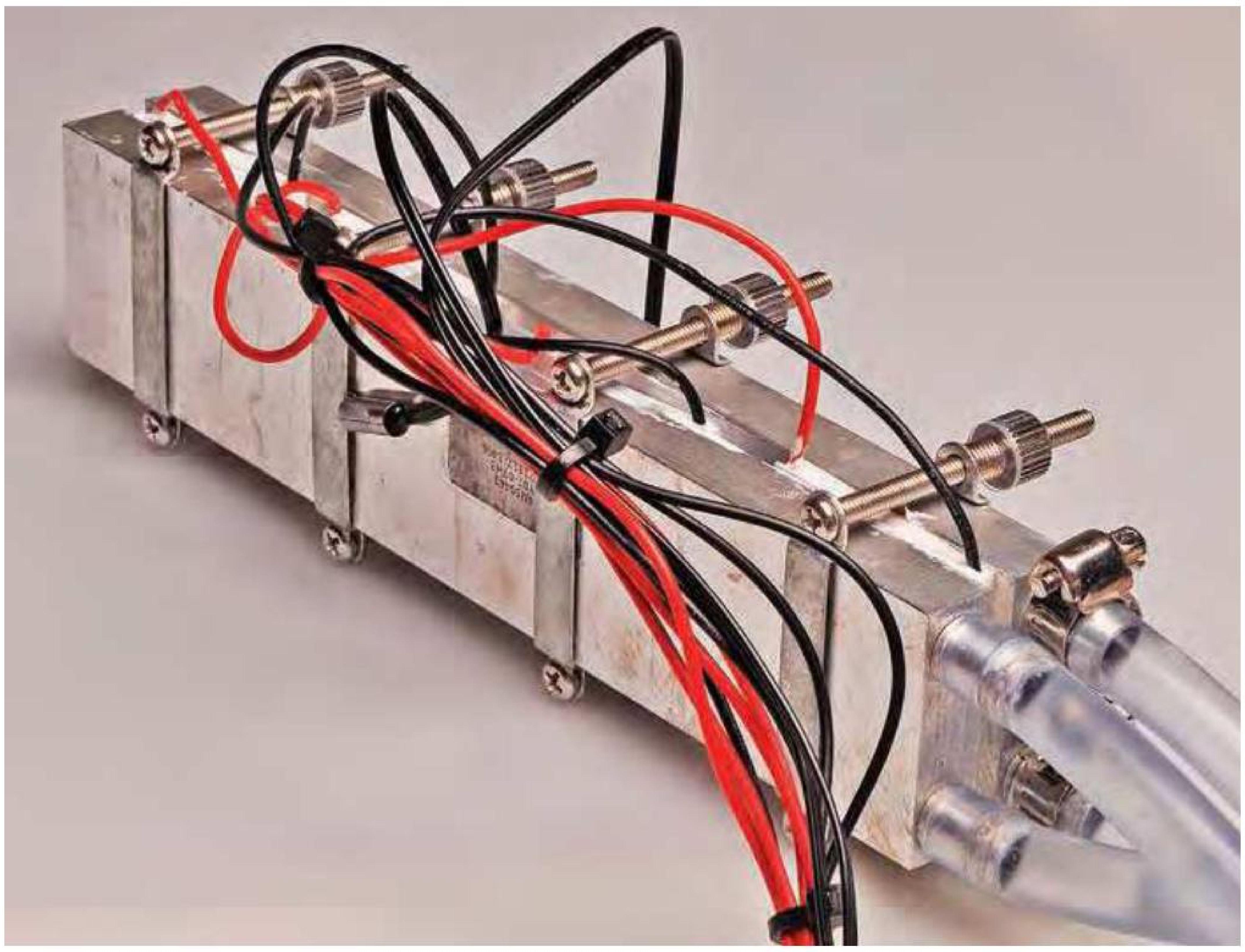
As we mentioned, the higher temperatures used for sous-vide cookery will tax the Peltier devices more. For this application, we recommend that you use a small foam cooler. We used one designed to hold six drink cans during testing. Its small size minimises the area through which heat is lost and also the volume of liquid to be heated. But it's large enough to fit most items you would cook.

These coolers can be found online or at disposals and outdoor stores. Check that it comes with a lid, as a fair degree of evaporation can occur at the temperatures used. You must also take care during use as the temperatures reached can be high enough to cause scalding.

Because the food is sealed into waterproof bags during the sous-vide process, there is minimal risk of contamination due to contact with non-food-safe parts. You might like to double-bag to be sure.

To implement the two-loop variant of our design, you will need a second vessel. The insulation on this is not so critical because the radiator and fans are simply trying to keep the second

The brass fittings are a snug fit for the transparent hose we used and did not show any signs of becoming detached. But we still used hose clamps to make sure. The tubing that was supplied with our kit with quite soft, so we replaced this with some thicker tube bought locally.



This assembly is held together by clamps, with the Peltier devices sandwiched between water blocks. The black wires visible lead to thermistors which are also held in place by the clamps. Not visible is a small amount of thermal compound between the heat-conducting surfaces.

loop's temperature near ambient anyway. It may be handy to have a lid, though, to prevent a long-term loss of water through evaporation. We used a plastic ice-cream tub as the second water vessel for our tests.

Another thing to be cautious about is the possibility of bacterial/algal contamination, particularly if you are using the *Thermal Regulator* for cooking. Bacteria and algae can flourish in warm water. For example, the circulation of warm water which is exposed to the air has been implicated in cases involving Legionnaire's disease, such as those found in industrial cooling towers.

Naturally, you should take care to prevent the water from the cooling loops coming near anything that may be consumed. You should also discard and replace the loop water regularly as this will help limit the accumulation of pathogens.

If you are familiar with the brewing process, then you will know how crucial proper cleanliness is for good, consistent results.

Measured performance

We found that under well-insulated conditions, our water bath got up to around 70°C with an ambient temperature of 18°C. For these tests, our main water vessel contained around two litres of water in an insulated foam cooler; the second loop was about a litre held in a (clean) ice-cream container.

In these tests, a good amount of water vapour is produced, resulting in evaporative cooling which forces the Peltier devices to work harder.

We got down to around 2°C when cooling. Getting close to the freezing point of water is the limiting factor. We saw frost on the Peltier devices, so it was clear that some parts were dropping below freezing.

The typical time to reach these extremes is about half an hour using four standard 5A devices running at around 11V. So you can see that the temperature ramp is not rapid. Good thermal insulation is necessary for reaching the temperature extremes.

We calculated that the secondary water loop cooled by the radiator has about double the heat removal capacity as the simple heatsink solution.

Consider that in all cases we are effectively trying to move heat between an ambient atmosphere (the air being circulated by the fans and through the radiator) and the water bath, the closer these temperatures are, the easier our task will be. Indeed, it is when the temperature differential across the Peltier devices is the largest that they struggle most.

For example, during some of our initial testing, while trying to cool hot water, we noted that it was more effective to shut down the Peltier devices and allow thermal conduction to move the heat. Powering the Peltier devices simply added more heat to the system (I^2R losses), which also had to be removed.

Sous-vide cookery is the application we envisage that requires the most extreme temperatures, so insulation is essential for good results there. In some cases, you could pre-heat the water using a kettle and then let the *Thermal Regulator* reach the target temperature and keep it there; that would be faster than starting with cold water.

Coming next month

That's all we have space for in this issue. Next month, we will describe how to build the two shields, program the Arduino and put the whole system together. In the meantime, if you want to build a *Thermal Regulator*, now

This radiator is more effective at removing heat than the heatsink and fans. This is due to its larger effective surface area.

A small foam cooler such as that shown here is a good choice for sous-vide cookery with the *Thermal Regulator*. A high degree of insulation is needed, and the snug-fitting lid minimises the amount of water and heat that is lost to evaporation.

Parts lists – Programmable Thermal Regulator (Arduino/Peltier)

1 set of fluid-handling hardware (see text and below)
1 Arduino Uno R3 or compatible (ATmega328-based) board
1 Peltier Driver shield (see below)
1 Interface shield (see below)
1 high-current DC power supply (see text)
1 20x4 alphanumeric LCD screen with I^2C interface (for example, the device in the June 2018 *PE* article)
1 length of light-duty figure 8 cable (for LCD screen)
1 4-way polarised header plug plus pins (for LCD screen)
1 universal infrared remote control
  [Jaycar XC3718, Altronics A1012]

Fluid-handling hardware (single loop)

4 5A Peltier devices
1 water vessel to suit your application
1 small 12V DC water pump
  [eg, **www.aliexpress.com/item/32810010753.html**]
1 40x200mm aluminium water block
  [eg, **www.aliexpress.com/item/4000299552495.html**]
1 water block mounting kit
  [eg, **www.aliexpress.com/item/32323128854.html**]
1 200mm-long heatsink (to suit water block)
  [Jaycar HH8530, Altronics H0536]
2 80mm 12V fans or to suit heatsink
  [Jaycar YX2512, Altronics F1050]
mounting hardware to suit fans
a few metres of 8mm internal diameter flexible silicone tubing
several elbows and tees to suit tubing
4+ 6-16mm hose clamps
1 tube of thermal paste
various cable ties

Fluid-handling hardware (twin loops)

4 5A Peltier devices
2 water vessels to suit your application
2 small 12V DC water pumps
  [eg, **www.aliexpress.com/item/32810010753.html**]
2 40x200mm aluminium water blocks
  [eg, **www.aliexpress.com/item/4000299552495.html**]
2 water block mounting kits
  [eg, **www.aliexpress.com/item/32323128854.html**]
a few metres of 8mm internal diameter flexible silicone tubing
several elbows and tees to suit tubing
8+ 6-16mm hose clamp
1 tube of thermal paste
various cable ties
1 fan radiator, 360mm type recommended
  [eg, **www.aliexpress.com/item/32833463954.html**]
1-3 12V fans to suit radiator (eg, 120mm fans)
  [Jaycar YX2574, Altronics F1165]
mounting hardware to suit fans

Peltier Driver shield parts

1 double-sided PCB coded 21109182, 53.5mm x 68.5mm
1 10-way stackable header (11mm pin height)
1 8-way stackable header (11mm pin height)
2 6-way stackable headers (11mm pin height)
2 2-way barrier terminals, 8.3mm pitch (CON1,CON2)
1 5x2-pin header (LK1-4)
3 jumper shunts (LK1-4)
2 M205 PCB-mount fuse clips (F1)
1 25A M205 fuse (F1)
1 3.3µH 19A SMD inductor, 14.0 x 12.8mm
  [eg, Pulse PA4343.332ANLT; Digi-Key 553-4025-1-ND]
4 M3 x 9mm machine screws
4 M3 hex nuts

Semiconductors
2 1N4148 small-signal diodes (D1,D2)
1 HIP4082 H-bridge driver, DIP-16 (IC1)
  [Digi-Key HIP4082IPZ-ND]
1 78L12, TO-92 (REG1; optional – see text)
4 IRLB8314 N-Channel MOSFETs, TO-220 (Q1-Q4)
  [Digi-Key IRLB8314PBF-ND]

Capacitors
3 100nF MKT or multi-layer ceramic
4 10µF 16V* X7R ceramic, 3216/1206 SMD package
  [Digi-key 1276-6641-1-ND]
  ** higher voltage versions required if DC supply >15V*

Resistors (all axial 1/4W 1% metal film)
2 10kΩ 1 1.8kΩ

Peltier Interface shield parts

1 double-sided PCB coded 21109181, 53.5mm x 68.5mm
1 10-way male pin header
1 8-way male pin header
2 6-way male pin headers
1 PCB-mount blade fuse holder (F1; optional)
1 2A blade fuse (F1)
5 2-way vertical polarised headers (CON1-CON5)
4 4-way vertical polarised headers (CON6-CON9)
3 5.08mm-pitch PCB-mount two-way screw terminals (CON10-CON12)
1 SPDT R/A PCB-mount toggle switch (S1; optional)
  [Altronics S1320]
1 3-pin header and jumper shunt (LK1)
1 6mm tactile switch (S2)
1 piezo buzzer (PB1) [Jaycar AB3459, Altronics S6104]
5 10kΩ/100kΩ NTC thermistors with cables
  [eg, **www.aliexpress.com/item/32916207487.html**
  or **www.aliexpress.com/item/33057351310.html**]
5 two-way polarised header plugs with pins (if thermistors don't come with a suitable plug)
light-duty figure-8 cable (if sensor wires are not long enough)

Semiconductors
1 74HC4053 triple 2-channel analogue multiplexer, DIP-16 (IC1)
1 DS18B20 digital temperature sensor, TO-92 (IC2)
2 BC337 NPN transistors, TO-92 (Q1,Q2)
1 BC547 NPN transistor, TO-92 (Q3)
1 red 5mm LED (LED1)
1 green 5mm LED (LED2)
1 blue 5mm LED (LED3)
3 1N4004 400V 1A diodes (D1-D3)

Capacitors
2 100nF MKT or multi-layer ceramic

Resistors (all 1/4W axial 1% metal film)
3 4.7kΩ 1 10kΩ 9 1kΩ 2 100Ω

would be a good time to figure out the system configuration you will need and order the parts. You may be able to start building the piping and heat transfer assemblies if those parts arrive quickly.

The software we'll present next month has several different operating modes: setting a target temperature which the unit then maintains, providing maximum heating or cooling, as well as one mode where it follows a preset temperature 'profile' when triggered.

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Dramatically improve performance of SDR – especially at HF

TUNABLE HF PREAMPLIFIER WITH GAIN CONTROL

by Charles Kosina

There are many cheap Software Defined Radio (SDR) modules available which perform brilliantly at VHF/UHF, but they generally have poor HF (3-30MHz) performance. They also suffer from wide-open front ends, which makes them susceptible to cross-modulation from strong signal sources. This simple tunable preamplifier greatly improves SDR HF performance. It has (optional) gain control and can run off a 5V supply or phantom power.

Most SDRs (and many other radio receivers) can benefit from a preamp to boost the signal from the antenna.

This one is nice and simple, low in cost, easy to build and works well over most of the HF range.

It can be built with variable or fixed gain. Variable gain is ideal as it allows you to avoid overload on strong signals, while still taking advantage of the improved selectivity of a tuned front end.

It's a fairly compact unit when completed, and runs from a 5V power supply, which in some cases can come from the receiver itself via the *Preamplifier's* output lead, using 'phantom power'.

The circuit of the *Tunable HF Preamplifier* is shown in Fig.1.

The input signal is fed into chassis-mount BNC connector CON1, then to the PCB via pin header CON2 and onto DPDT switch S1, which passes it to one of two transformers. This provides two different tuning ranges, allowing the tuning to be more selective.

T1 covers a range of about 5-11MHz, while T2 covers 11-24MHz. Both are tuned by dual variable capacitor VC1, with its two gangs wired in parallel to give a 6-200pF range.

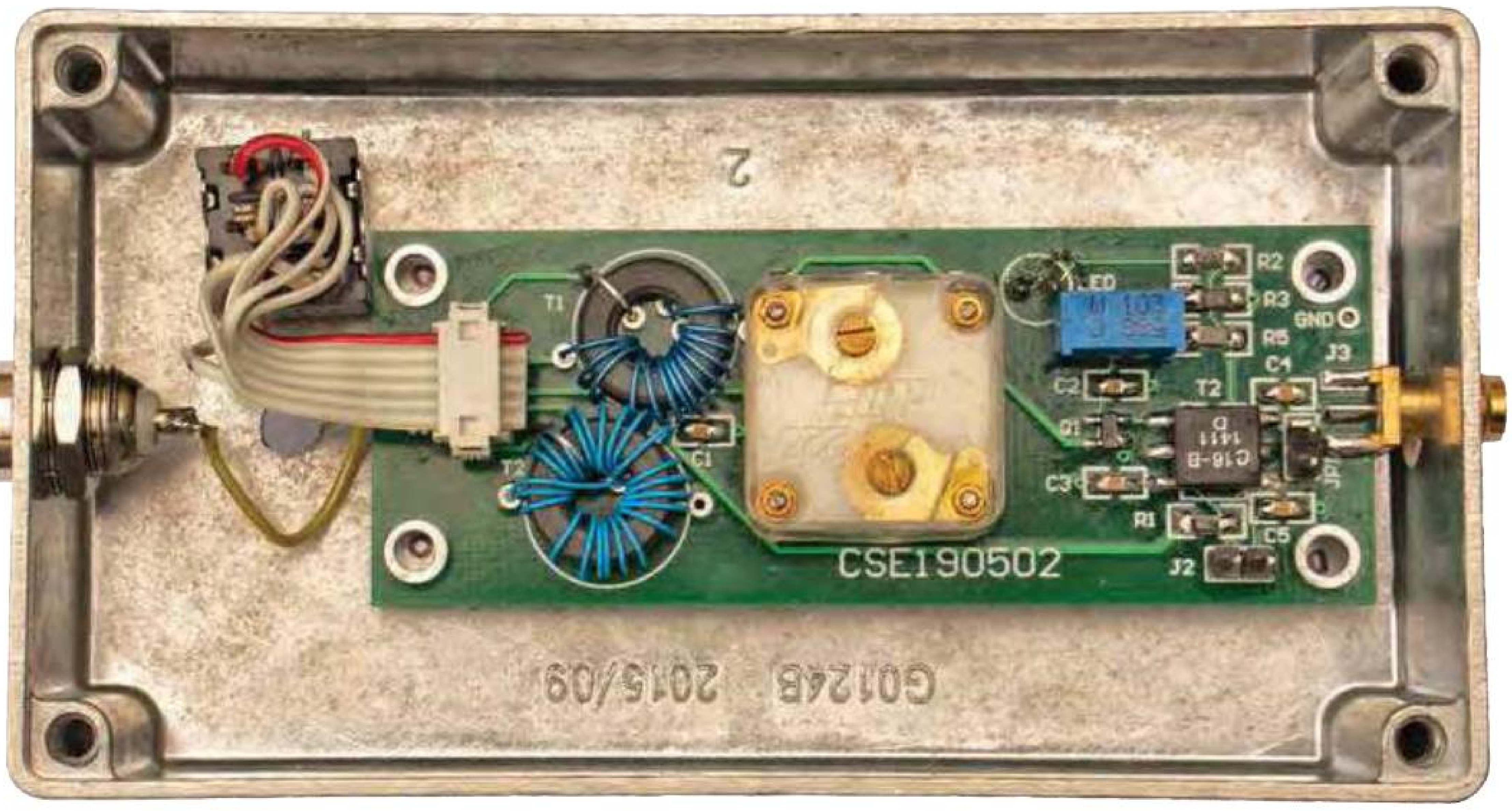
The tuned signal is then fed to gate 1 of dual-gate MOSFET Q1. The signal is DC-biased from the nominally +5V rail via a 150kΩ resistor and 10nF low-pass filter capacitor, to reject supply noise.

The MOSFET's gain is controlled by varying the DC voltage on the second gate, using potentiometer VR1 which has padder resistors at either end, to limit its wiper voltage to the useful range.

Fixed gain can be provided by omitting VR1 and changing the resistor values, as described in the circuit diagram.

Q1's drain load is the primary of transformer T3, with a 1.25mH inductance. The other end connects to the +5V rail which is bypassed by a 10nF capacitor. The 75µH secondary is connected similarly, and the signal is AC-coupled to output SMA connector CON3 via another 10nF capacitor.

Alternatively, if you want the device to be phantom powered via CON3, jumper JP1 is inserted, allowing the DC supply voltage to flow through T3's



Shown a little larger than life size, this is the completed PCB (in this case version 1 with toroids) mounted in the diecast case. S1 is shown here mounted off the board, but the Altronics S2075 slide switch could probably be mounted directly.

Features and specifications

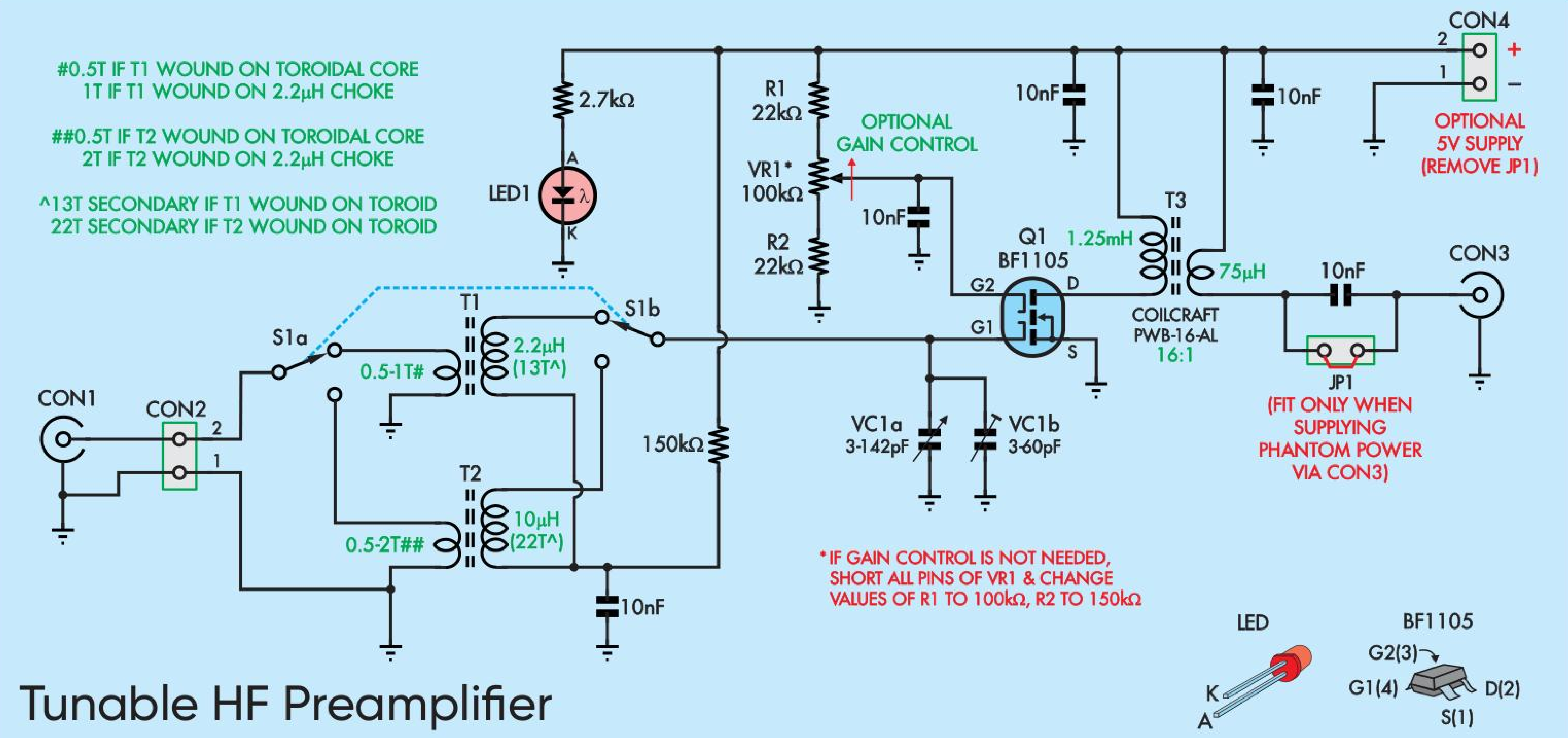
Tuning range *...5-24MHz (two ranges, wider tuning range possible)*

Bandwidth *........typically 50-250kHz (varies with tuned frequency)*

Gain *.................typically 34-36dB*

Power supply *...5V DC @ 30mA*

Connectors *......BNC input, SMA output (can be varied)*



#0.5T IF T1 WOUND ON TOROIDAL CORE
1T IF T1 WOUND ON 2.2µH CHOKE
##0.5T IF T2 WOUND ON TOROIDAL CORE
2T IF T2 WOUND ON 2.2µH CHOKE
^13T SECONDARY IF T1 WOUND ON TOROID
22T SECONDARY IF T2 WOUND ON TOROID
2.7kΩ
LED1
A
K
λ
R1
22kΩ
VR1*
100kΩ
R2
22kΩ
OPTIONAL
GAIN CONTROL
10nF
10nF
10nF
CON4
2
1
+
–
OPTIONAL
5V SUPPLY
(REMOVE JP1)
T3
1.25mH
75µH
Q1
BF1105
G2
G1
D
S
COILCRAFT
PWB-16-AL
16:1
10nF
CON3
JP1
(FIT ONLY WHEN
SUPPLYING
PHANTOM POWER
VIA CON3)
S1a
S1b
T1
2.2µH
(13T^)
0.5-1T#
CON1
CON2
2
1
T2
10µH
(22T^)
0.5-2T##
150kΩ
10nF
VC1a
3-142pF
VC1b
3-60pF
*IF GAIN CONTROL IS NOT NEEDED,
SHORT ALL PINS OF VR1 & CHANGE
VALUES OF R1 TO 100kΩ, R2 TO 150kΩ
LED
K
A
BF1105
G2(3)
G1(4)
D(2)
S(1)
Tunable HF Preamplifier

Fig.1: the circuit is quite simple, especially given its performance. It has a gain of around 35dB and a tuning range up to about 24MHz as shown (but can be extended to about 30MHz). VC1 a and b is a miniature dual variable capacitor, typically sold as a tuning capacitor for small radio receivers.

secondary and into the +5V rail. This is then modulated with the output signal which is coupled in from T3's primary.

Two versions

You can build the device in two different versions. Version 1 has T1 and T2 wound on toroidal ferrite cores. These are not that easy to get, and winding the turns is tedious, but they have the advantage of a very high unloaded Q, up to 350.

Version 2 is easier to build as T1 and T2 are based on readily obtainable axial RF inductors, which are each about the size of a 1W resistor.

The primary winding is just one or two turns of wire around the inductor body. These inductors exhibit a surprisingly high Q, up to 120 in the range of interest.

Obtaining the parts

The output transformer is a broadband Coilcraft device. I got mine as a free sample, but they are also readily available from element14. The tuning capacitor comes from Jaycar and many other sources, including eBay. The SMA output connector is readily available on eBay; sellers often list ten for a few pounds.

The other components are reasonably standard parts. Those which are not available from Jaycar or Altronics can be purchased from Digi-key, Mouser or element14.

Changing the frequency range

If you changed the 2.2µH inductor to 1µH, that would give you a tuning range of about 12-30MHz, giving you almost full coverage of the HF band. If building Version 1, with the toroidal ferrite cores, this could be achieved by reducing the number of secondary windings on T1 by about one third. If building version 2, using RF chokes, simply substitute a 1µH choke.

Construction

The *Tunable HF Preamplifier* is built on a double-sided PCB coded CSE190502, measuring 79.5 x 29mm. Refer to the overlay diagram, Fig.2, along with the photos to see how it all goes together.

Fig.2(a) shows Version 1, with T1 and T2 wound on ferrite toroidal cores, while Fig.2(b) shows Version 2, using the RF chokes with turns of wire around the outside of each to make them into transformers.

We used 0.25mm insulated wire but enamelled copper (ENCU) wire would also be satisfactory.

Many of the components are SMDs, with 2012 (metric) / 0805 (imperial) capacitors and 3216 (metric) / 1206 (imperial) resistors.

I find that an SMD board now takes me less time to assemble than one with through-hole components, and none of the parts on this board are difficult to solder.

Start by fitting the SMD passives. Tack one end down, then solder the other end and wait for the joint to solidify before refreshing the first joint. Then mount dual-gate MOSFET Q1 with its larger tab oriented as shown above, followed by transformer T3, with its pin 1 dot at upper left.

Follow with edge-mount connector CON3, which is placed over the edge of the board before soldering its pins top and bottom. Make sure the middle contact pin is on the correct side to match with its pad. Then fit the pin headers where shown.

If you are building Version 1, now is the time to wind and mount the toroidal transformers. T1 has a half-turn for its primary (best fitted after the secondary has already been soldered to the board) and 13 equally-spaced turns for its secondary. Try to wind the secondary so that it spans just over half the core, meaning the start and end correspond with the PCB pads (see photos).

T2 also has a half-turn primary but a 22-turn secondary, which is wound to cover the entire circumference of the core (not shown for clarity in Fig.2(a); see the photo) and then brought back across the core to terminate to the other secondary pad on the PCB.

Once you've wound the secondaries and soldered them to the PCB pads, you can solder one end of each primary, pull it tight across the core and then trim it and solder the other end.

If you're building Version 2, you just need to wind one turn of 0.25mm wire (ENCU or insulated) around the body of the 2.2µH inductor and fit it for T1 as shown, with the added windings as the primary, and wind two turns around the 10µH inductor and use it as T2; again, the added windings are the primary.

If you're using a trimpot for VR1, fit it now. If you want the gain to be externally adjustable, solder leads onto the three terminals of your chosen potentiometer and attach a three-pin plug to the other end. Alternatively (and more simply), cut female-female jumper leads in half and solder the exposed ends to the pot terminals. The

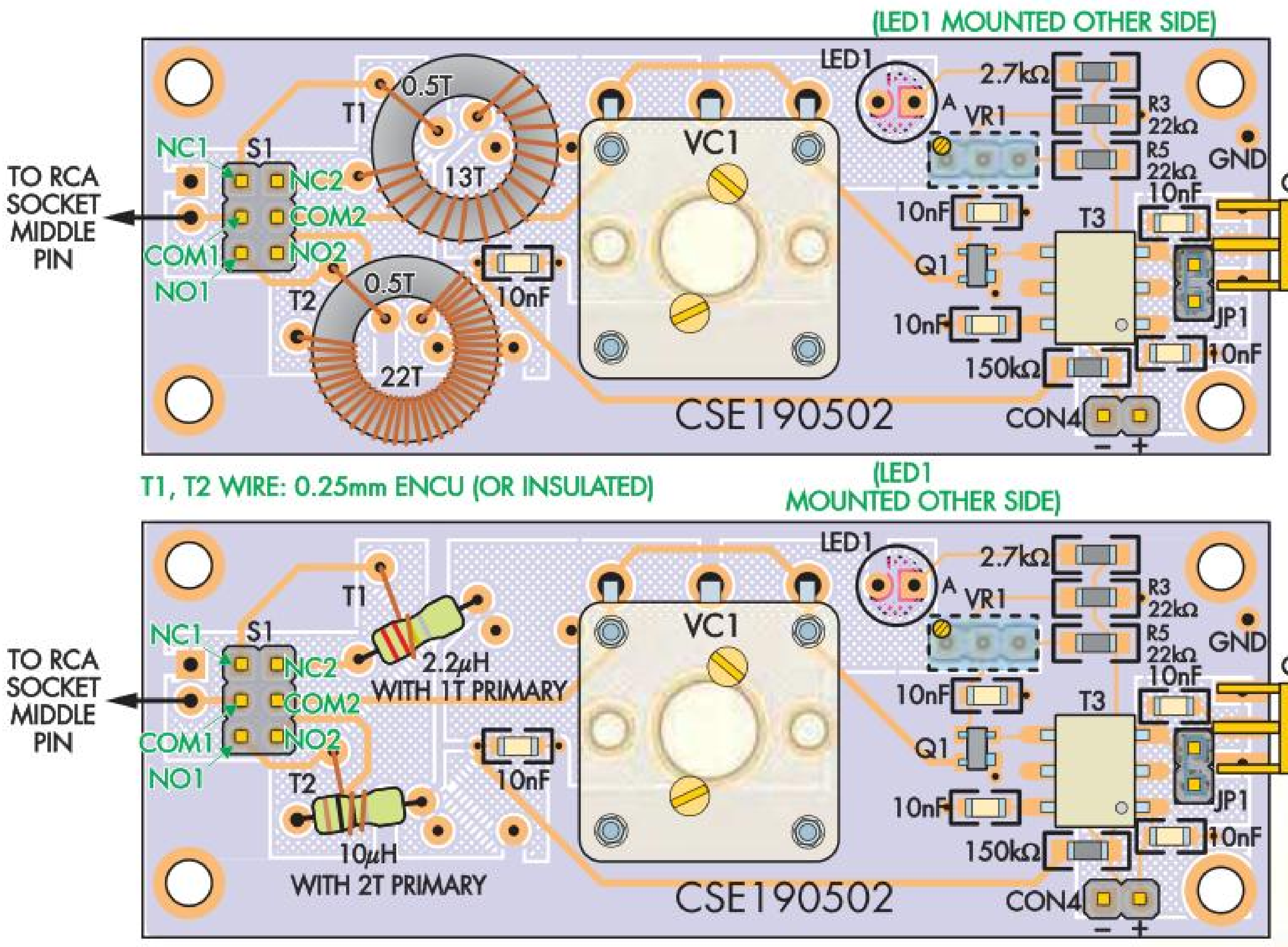
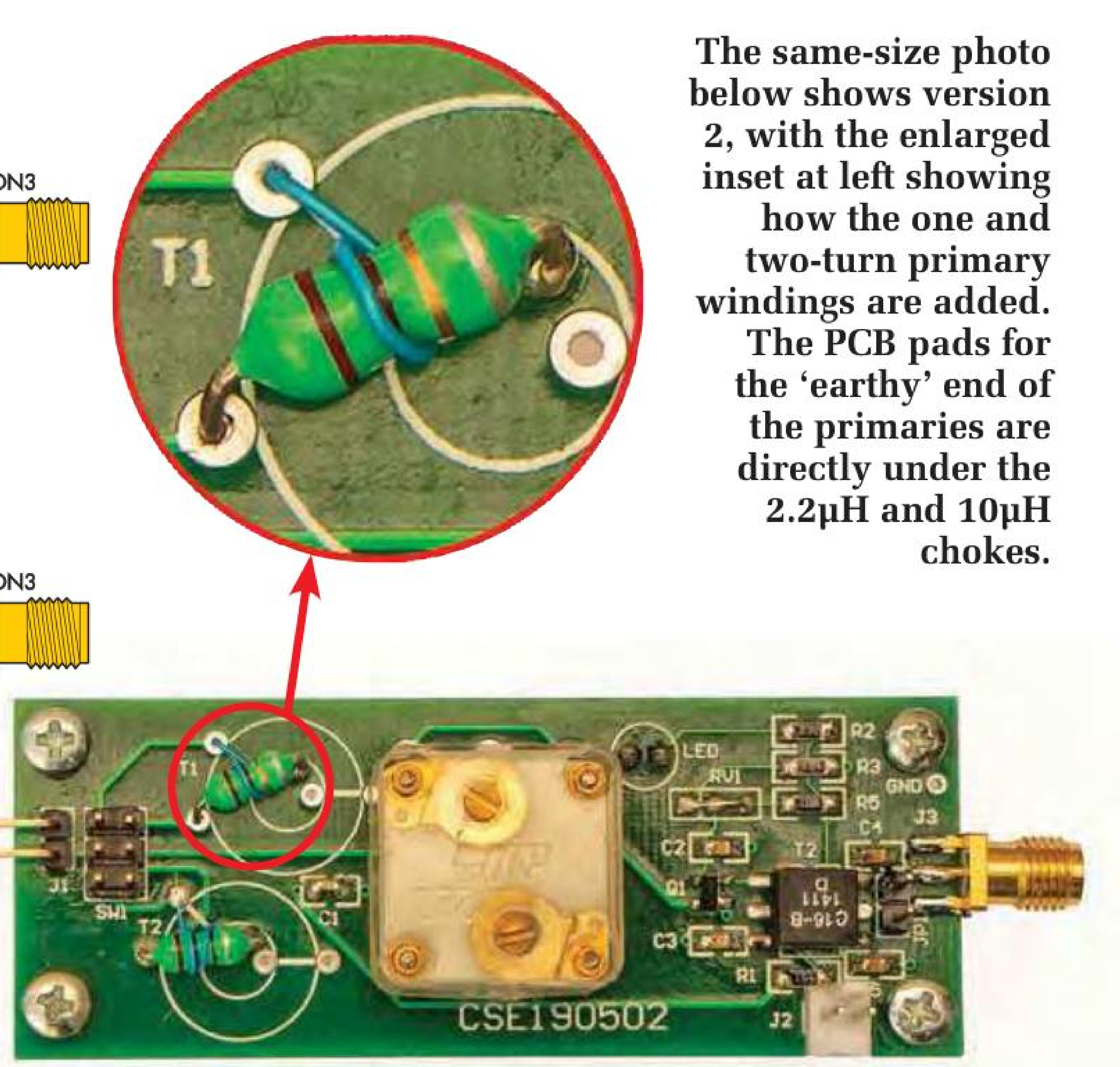


Fig.2a (top) is the component overlay for version 1, using two toroids for T1 and T2 with primaries and secondaries wound through them. Fig.2b (bottom) shows version 2, an identical overlay but using axial RF chokes instead, with primaries of one or two turns of thin wire around them.



The same-size photo below shows version 2, with the enlarged inset at left showing how the one and two-turn primary windings are added. The PCB pads for the 'earthy' end of the primaries are directly under the 2.2μH and 10μH chokes.

sockets at the other end can be plugged into the PCB header later.

Now fit the variable capacitor. Remove the knob first, then attach the body to the PCB using the two supplied screws through from the underside. Solder the three pins, then re-attach the knob to the shaft, which passes through a hole in the PCB.

Leave LED1 off for now.

Preparing the case

Now place the PCB assembly in the case, sitting on its spacers, and slide it so that CON3 touches the side of the case. Measure the distance from the centre of CON3 to the top of the box. Then measure that same distance on the outside, from the top of the box near CON3, and mark where the hole will need to be drilled. Remove the PCB and drill a small hole there, then enlarge it to 7mm.

Check that the connector fits through the hole with the spacers sitting on the bottom of the box. If so, deburr it. Otherwise, you may have to enlarge it slightly. Once it fits, drill a small hole at the opposite end of the box and enlarge it to around 10mm, then check that the BNC socket fits. Once it does, deburr that hole too and again, clean out the swarf.

Now remove the spacers from the PCB, push CON3 through the hole you drilled and mark out the four mounting hole positions. Also mark the location where LED1 will protrude through the base, once it has been installed, and mark a suitable location for the DPDT switch. Note that a 5mm LED will have to clear the PCB once fitted.

Drill the marked holes to 3mm, then enlarge the LED hole to 5mm, and the switch hole until the switch fits. Deburr all the holes and clean off the swarf. If you're building the *Preamplifier* with an external gain control, now is also a good time to figure out where the pot will be mounted and drill and deburr a suitable hole.

If you are going to be supplying external power, drill a hole for the DC socket now. It would make sense to move the BNC socket slightly towards one side of the case to make more room for the DC socket.

Final assembly

The last component to be fitted to the board is the LED. It's mounted on the opposite side to most of the other components, and its longer lead must face towards the pad marked 'A' on the PCB.

Push its leads through their holes so that the lens is fully down onto the PCB, then slot the board in place hold-

Parts list – Tunable HF Preamp

1 double-sided PCB, code CSE190502, 79.5 x 29mm
1 diecast aluminium case, 115 x 65 x 30mm [Jaycar HB5036, Altronics H0421]
1 BF1105 dual-gate SMD MOSFET (Q1)
1 5mm or 3mm LED (LED1)
2 small toroidal ferrite cores, 12.5mm OD, 7.5mm ID, 5mm thick (T1/T2) [eg, TDK B64290A0044X830] ***OR***
2 axial RF chokes, 2.2μH and 10μH [Jaycar LF1514 + LF1522, Altronics L7014 + L7022]
1 Coilcraft PWB-16-AL transformer (T3) [mouser.co.uk, element14]
1 chassis-mount BNC socket (CON1)
1 edge-mount SMA socket (CON3)
3 2-pin headers (CON2,CON4,JP1)
1 chassis-mount DC socket (optional)
1 shorting block/jumper shunt (for JP1)
1 DPDT toggle or slide switch (S1)
1 3-pin header (for VR1)
1 3x2-pin header (for S1)
4 6.3mm nylon M3 tapped spacers
8 M3 x 6mm machine screws
1 1m length of 0.25mm diameter enamelled copper or insulated wire
1 1m length of light-duty hookup wire
1 50mm length of 6-way ribbon cable (for S1)
1 6-pin IDC socket (for S1)

Capacitors
5 10nF 50V SMD ceramic capacitors, 2012/0805 size, X7R dielectric
1 dual variable capacitor (VC1) [Jaycar RV5728, ebay item 362011911185, bitsbox.co.uk, VC006]

Resistors (all SMD 3216/1206 size, 1%)
1 150kΩ 2 22kΩ* 1 2.7kΩ
1 100kΩ linear chassis-mount potentiometer (VR1) ***OR***
1 100kΩ multi-turn vertical trimpot (VR1)

* or 1 100kΩ + 1 150kΩ for fixed gain (omit VR1 and 3-pin header)

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ing the leads, and use them to push the LED lens through its mounting hole while CON3 is hard against the edge of the case.

Prop the board up so that the LED lens is not being pushed back into the hole, attach a couple of the board mounting screws to ensure it's in position, then solder and trim LED1's leads. After that, insert the remainder of the PCB mounting screws.

Mount the BNC socket in the hole you made earlier and solder a short length of hookup wire to its middle pin. Connect this wire to the lower terminal of CON2, to the left of the header for S1, as shown in Figs.2(a) and (b). You don't need to connect the RCA socket shield, as it's grounded to the metal box and this connects to board ground via CON3's shell.

All that's left now is to wire up and fit switch S1. Crimp a length of 6-way ribbon cable into the IDC connector shell, so that the red wire will be towards the top when plugged into the header on the board such that the cable exits to the left (ie, towards the nearest board edge).

Now separate and strip the wires at the other end. Starting with the red wire, solder them to the following switch terminals: NC1, NC2, COM1, COM2, NO1, NO2. In this case, the numbers 1 and 2 refer to the two switch poles. It doesn't matter which is 1 and which is 2, as long as you are consistent. It also doesn't matter which side of the switch you consider to be NC and which is NO.

Once the wires have been soldered and the switch mounted in the base, plug the IDC socket into the header as shown in the photos.

If using a DC socket to feed in external power, solder wires to its two tabs; if your socket has three tabs, plug in a plugpack and use a DMM to figure out which is positive and which is negative. Mount the socket in the hole you made earlier, then terminate the leads to CON4, either by soldering them directly to its pins (see PCB for polarity) or by attaching a two-way header socket to the wires.

As with the pot, you can cut a female-female jumper lead in half and then solder its bare ends to the DC socket. The other ends will plug straight into CON4. Alternatively, if using phantom power from the radio receiver via CON3, place a jumper shunt on JP1 now.

If you're fitting an external gain control pot, mount this now, and plug its terminals into the pin header soldered in place of VR1. The lead soldered to the anti-clockwise end of the pot (as viewed from the front) plugs into the left-most terminal of the VR1 header, with the PCB viewed right-side-up.

Using it

Now it's just a matter of screwing the lid onto the box, connecting your antenna to CON1, your radio to CON3, hooking up a 5V power supply (if using external power), and switching S1 to the appropriate band. You may wish to label the case to indicate which position is for the lower tuning range and which is for the upper.

With power applied, check that LED1 lights. Switch to your SDR's spectrum analyser view and set the range to 3-30MHz. Check that adjusting VC1 changes which frequencies are being amplified, and that VR1 (if fitted) allows you to control the gain. Check also that S1 switches bands and that the two ranges are roughly as expected.

As VC1 is not calibrated, you will need to use a spectrum display to see what frequency you are tuning in, although you can 'blind tune' by simply adjusting VC1 and S1 for maximum signal at your desired frequency.

Then adjust VR1 (if fitted) for the best reception without overloading the receiver.

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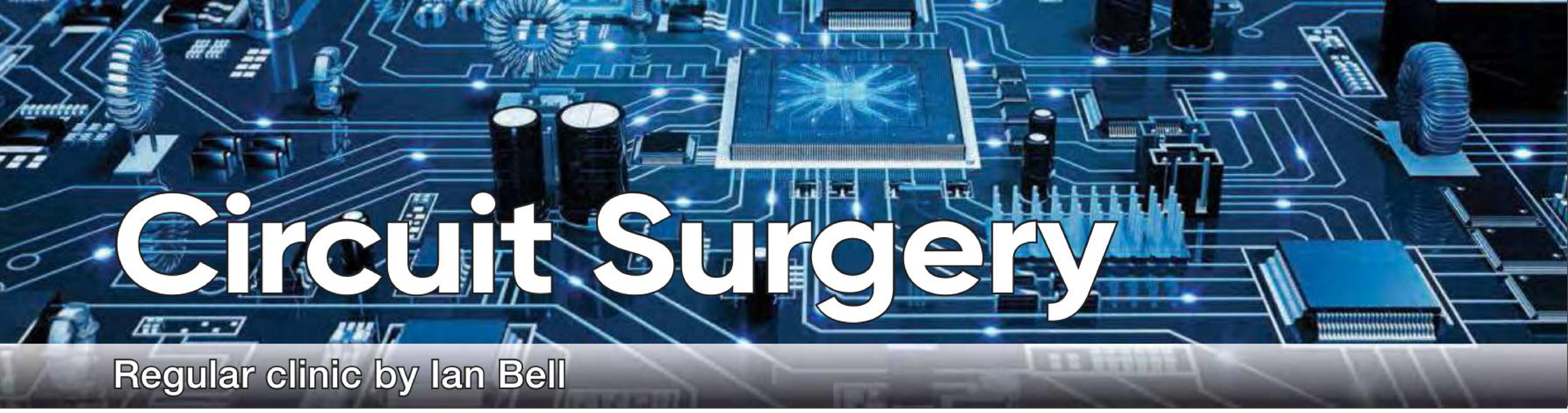

Circuit Surgery

Regular clinic by Ian Bell

Timing and metastability in synchronous circuits – Part 1

Last month, we looked at a digital (frequency) divide-by-two circuit from Ken Wood. Ken found that his circuit operated correctly when constructed, but a simulation in Micro-Cap 12 oscillated. Ken was inspired to try the simulation after reading in *Circuit Surgery* (December 2020) that this one-time $4500 professional software had been made freely available in July 2019.

Ken's problems raised some interesting issues. First, the fact that unexpected simulation results can occur in some situations where two or more components are *identical*, leading to very specific circuit behaviour – these results are not really wrong, but may be extremely unlikely to occur in a real circuit. It was equal gate delays in Ken's simulation that created the conditions for oscillation. Second, looking in more depth at what might happen in Ken's circuit we identified the possibility of metastability in an SR flip-flop. A flip-flop should either store a 0 or a 1 (its stable states), quickly updating when required. Metastability can be thought of as flip-flop 'indecision' – it gets stuck half-way between 0 and 1, and takes much longer than usual before finally settling in one of the stable states. We saw this in LTspice analogue simulations of a flip-flop storage loop last month.

Ken's circuit was unusual in that he was specifically trying to create the divide-by-two circuit directly from a minimum number of NAND gates, using asynchronous design techniques, rather than just using an existing flip-flop. Our focus last month was on the specifics of Ken's circuit; however, metastability, and timing issues in general, are important when working with the much more common situation of synchronous digital circuits built from clocked flip-flops and larger blocks such as registers and counters. This month, we will look at timing and metastability in the context of synchronous digital circuits. We will start by looking at the general structure of these circuits and the timing conditions needed to make sure they operate correctly.

Synchronous circuits and clocks

The majority of digital circuits have one or more clocks – a regular train of pulses that controls the overall timing of (that part of) the circuit. The clock is like a drill sergeant who is barking 'left, right' at a group of soldiers so they all march in a synchronised fashion. Circuits whose timing is coordinated by a clock are described as 'synchronous' – this applies to the majority of digital circuits. We often break larger circuits down into smaller blocks or subsystems, and in the simplest cases these will all have the same clock. Fig.1 shows a simple example – real circuits will usually have a more complex structure.

Often, the clock is basically a square wave at a specific, often accurately controlled frequency. In simple systems, the clock frequency may be fairly arbitrary, but in other cases may be determined by very specific constraints; for example, for visual display signals or data communication protocols. A complex system may have a number of such subsystems requiring different timing, and therefore may have multiple clocks (see Fig.2). The circuitry associated with a given clock is said to be in a particular clock domain. Transferring data across clock domains must be done carefully to avoid potential timing problems and consequent errors.

Digital circuit operations that are not under the timing control of the clock are described as 'asynchronous'. Circuits can be mainly synchronous but also feature some asynchronous operations or functions. Perhaps the most common example is an asynchronous reset, which puts the circuit into a well-defined state at power up, or after a crash when a user 'hits the reset'. Asynchronous resets are common in flip-flops and other devices in the 4000 and 7400 logic families; however, resets can also be synchronous.

It is common for external inputs to clocked digital systems to be asynchronous – the external system will not be related to the internal clock timing unless the system's clock is from a source where it is already coordinated with the other inputs. The fact inputs are often asynchronous, and therefore may change at the 'wrong' time, means that there is always the potential for timing problems to occur – more on this later.

The circuit in Fig.1 is synchronous. The operation of each stage is stepped forward by a specific transition of the clock (0 to 1, or 1 to 0) – known as the active clock edge – thus all operations are synchronised by the clock. The fact that an edge triggers the operation is often indicated by a small triangle next to the input on the circuit symbol for the block/component, as in Fig.1 to Fig.3. If there is a small circle ('inversion bubble') between the triangle and input wire a negative edge trigger (1 to 0) is indicated, otherwise the edge trigger is positive (0 to 1). Block symbols for positive and negative edge-triggered circuits are also shown in Fig.3 – the blocks could represent individual flip-flops or larger more complex circuits.

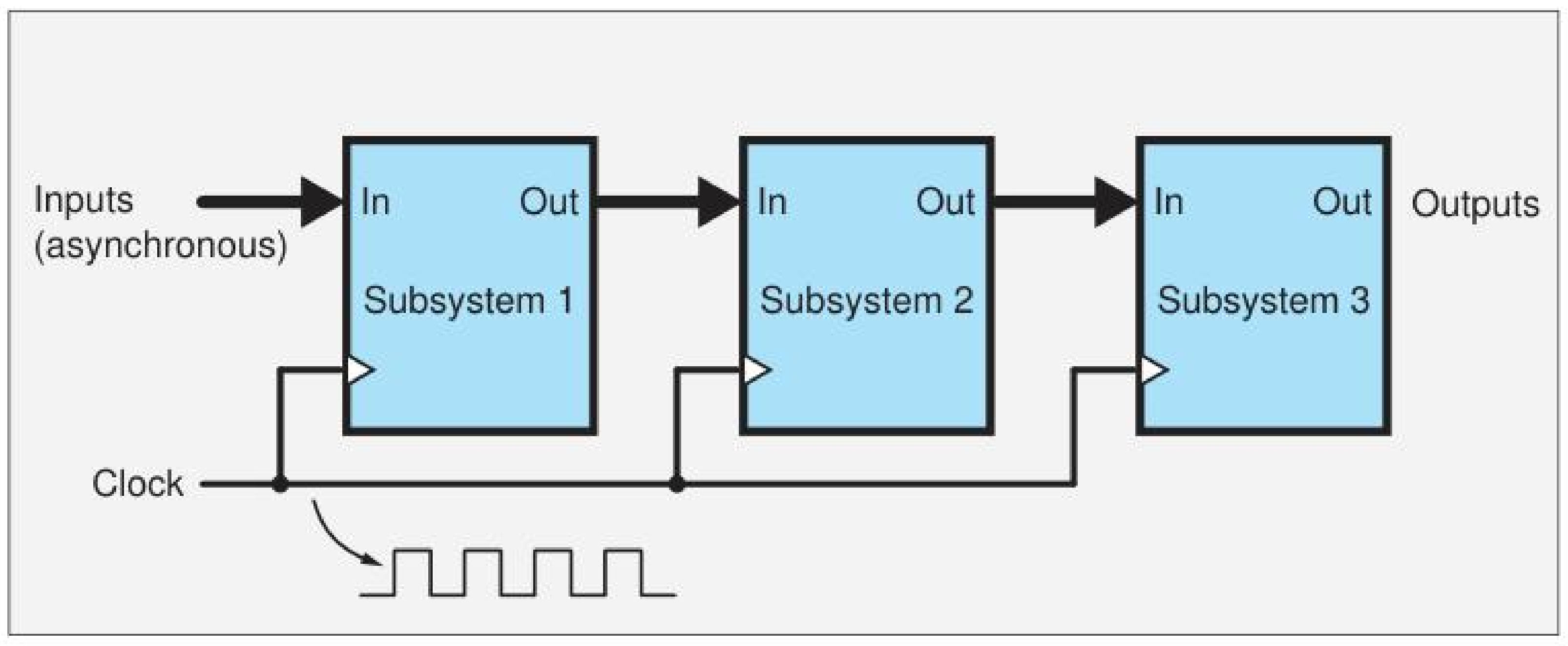

Fig.1. Single-clock subsystem drawn as a block structure.

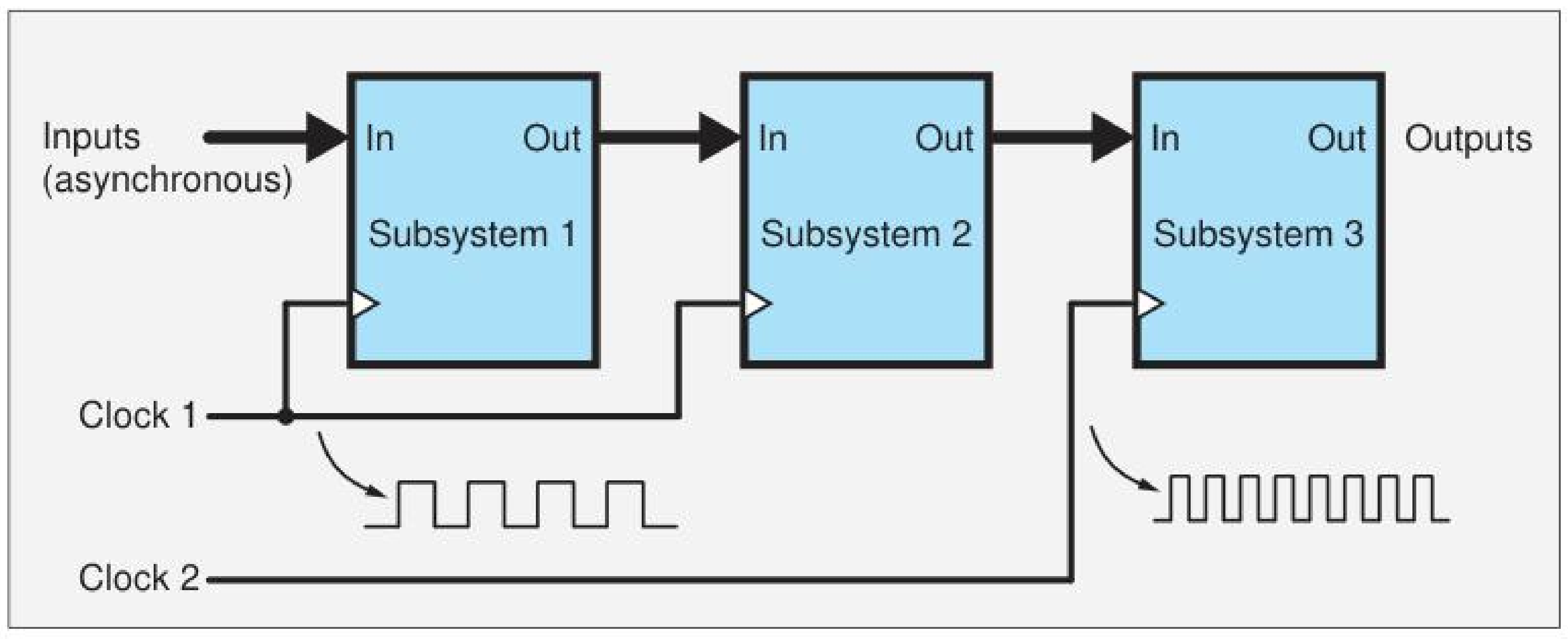

Fig.2. Synchronous system with more than one clock domain.

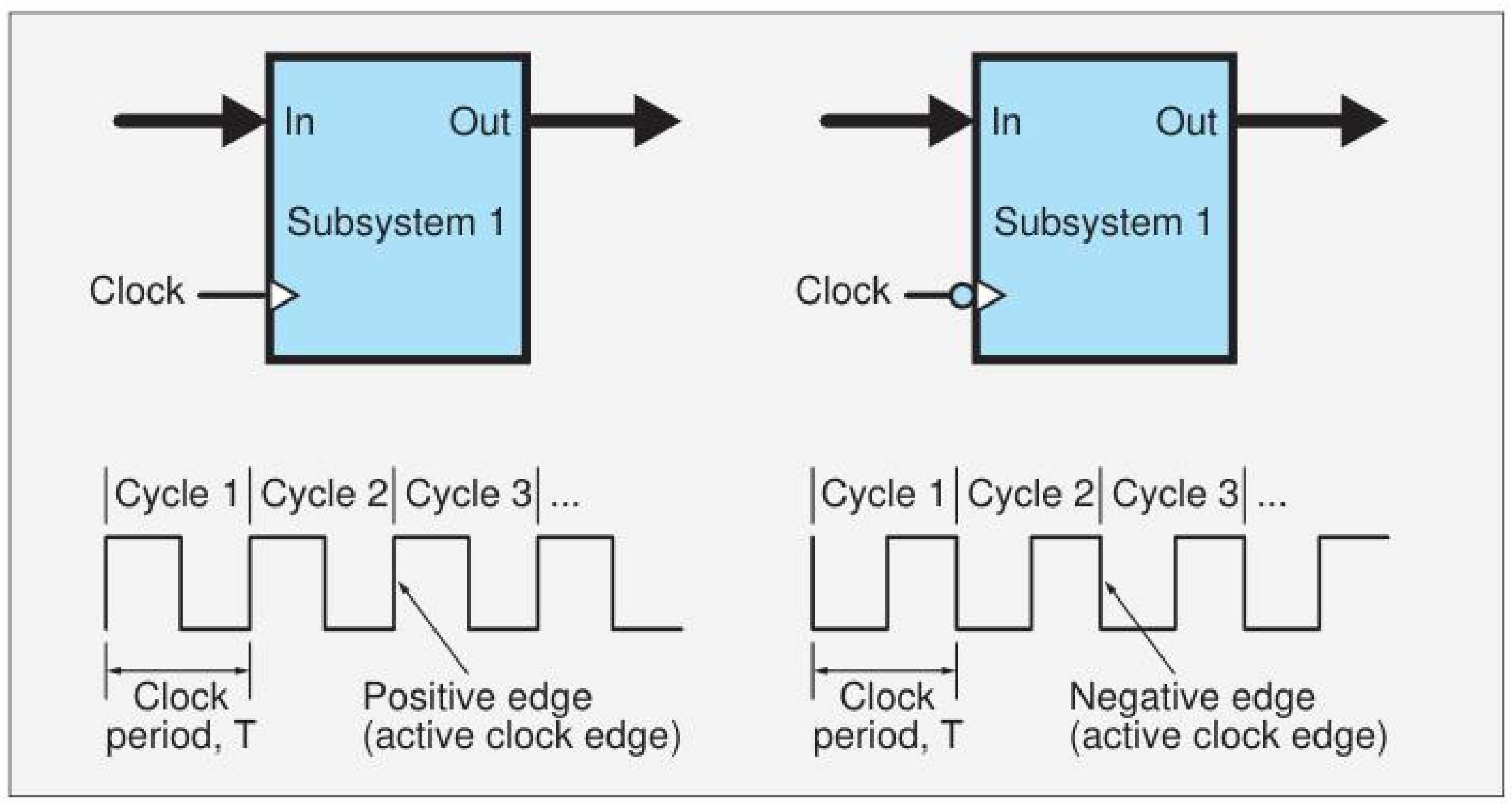

Fig.3. Some definitions relating to clocks.

The repeating part of a clock waveform is referred to as the clock cycle. If circuit activity is edge triggered then the cycle is usually considered to start at the active clock edge. Clock waveforms with clock cycles identified, for both positive and negative edge systems, are shown in Fig.3. The time duration of one clock cycle is called the clock period, T_C. The frequency of the clock is given by: $f_C = 1/T_C$.

The stages (in Fig.1) operate simultaneously, so stage 1 is processing new data while stages 2 and 3 work on older information. This is a bit like an assembly line in a factory, where the finishing touches are applied to one copy of a product at the end of the line simultaneously with starting the production of another copy at the other end (and simultaneously with all the intermediate steps on other copies too). The clock sets the points in time when all 'items' (information) on the 'production line' move from the current stage to the next. As indicated above, the structure of real circuits is often more complex than that shown in Fig.1 and Fig.2, with feedback and feedforward of information, and multiple different paths through the system, rather than the simple 'straight through' structure depicted in Fig.1 and Fig.2. However, a simple structure is sufficient for our purpose of discussing the basics of timing in synchronous circuits.

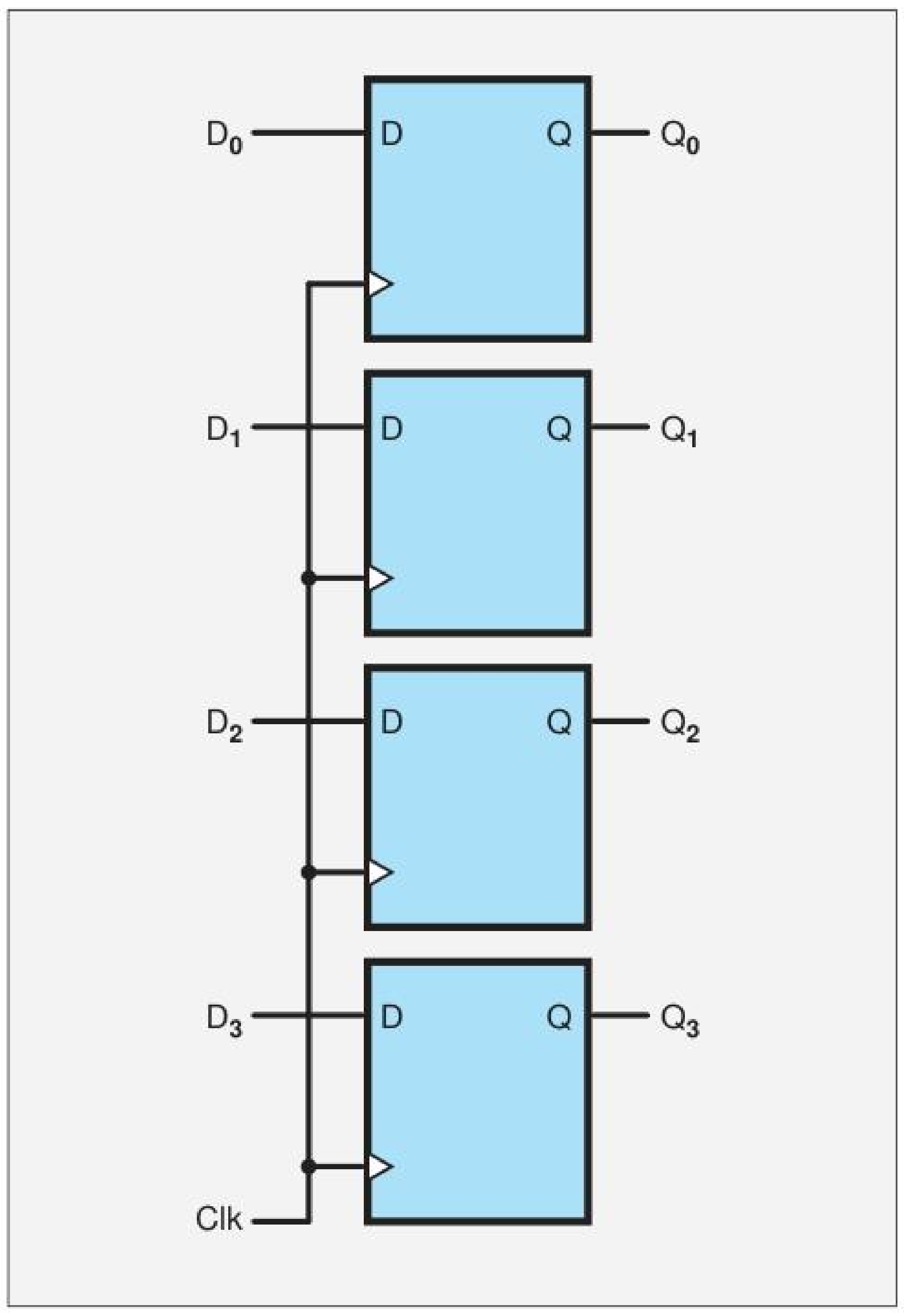

Fig.4. A four-bit register built from D-type flip-flops.

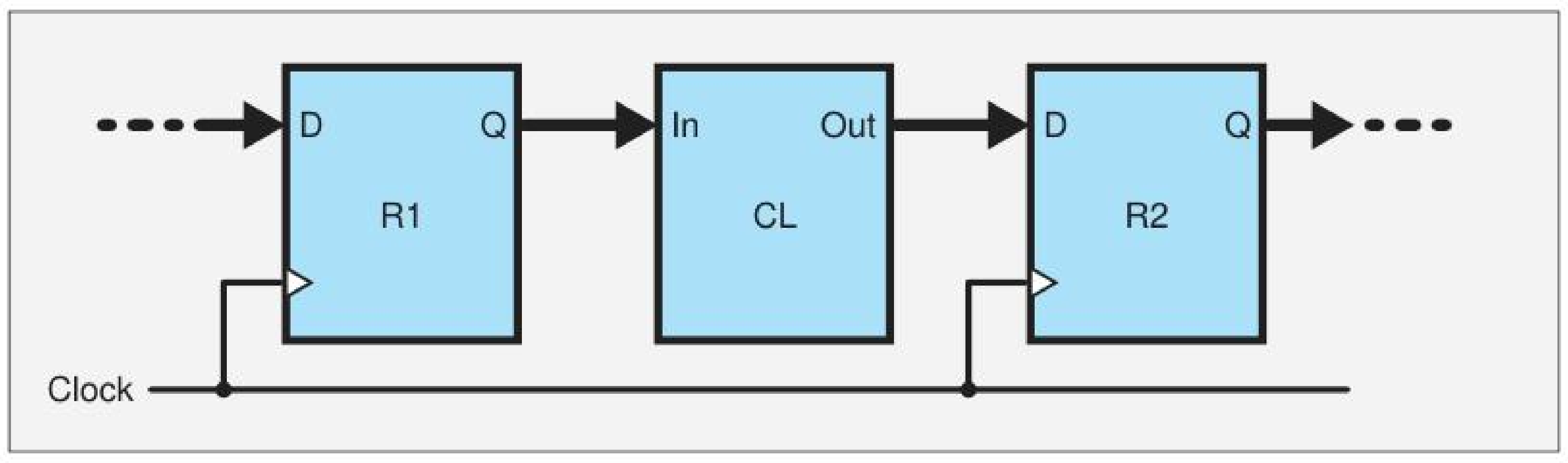

Fig.5. Register-to-register transfer (R1, R2) via a block of combinational logic (CL) is the key structure in a synchronous circuit.

Although the production line analogy does not quite fit more complex structures, it reminds us of the step-by-step processing and the fact that it takes a number of clock cycles before an input at a given time will influence values inside the circuit and at the output. This processing delay is referred to as latency and should not be confused with throughput, which is the number of new input values/conditions per second the circuit can handle – often equal to the clock frequency.

Register to register

In order to consider the timing in more detail we need a slightly lower-level picture of the typical circuit structure than provided by Fig.1, where each block could have a complex internal structure. In general, a synchronous digital circuit comprises data storage, called registers, and function blocks which manipulate information. The function circuits are implemented with combinational logic. Combinational logic circuits do not contain any memory elements (flip-flops or latches) so their outputs depend only on the current value of their inputs. Registers are sets of D-type flip-flops – one for each bit of data stored (see Fig.4). Of course, other types of flip-flop can be used in circuits, but the same basic principles of timing will apply.

The functions are many and varied and include coding, decoding, finding the next value in a sequence and arithmetic functions such as adding. The information being processed by any function circuit is held in one or more registers connected to its inputs and the results, when ready, are stored in one or more resisters connected to the function block outputs. This is illustrated in its simplest form in Fig.5, where register R1 holds the data being worked on by the combinational logic CL, and R2 holds the results. This circuit is suitable for defining timing requirements in synchronous digital circuits.

For the circuit in Fig.5, when the active clock edge occurs the register R1 loads new data. Specifically, the data on its D inputs is stored in the register and appears at its Q outputs. The register is not infinitely fast, so its outputs change a short time after the clock edge, this is referred to as the propagation delay of the register (we will call it T_{DR}). Given that the register is typically a set of identical flip-flops, we can often assume that all its outputs update at more or less the same time.

In Fig.5, when register R1 updates the inputs to the combinational circuit change, and after some time, its outputs will respond. Unlike the register, we cannot generally assume that all combinational logic outputs change at about the same time, in fact each output bit may change several times, producing various intermediate output values for a while, until all the effects of the input change have propagated though and the circuit settles. These intermediate outputs are called hazards or glitches. In terms of timing, we are mainly interested in the longest possible time the combinational circuit will take to fully settle in response to any input change. This value is referred to as the propagation delay of the circuit (we will call it T_{DCL}). Unless the circuit has been specifically designed to be guaranteed 'hazard-free', we generally have to assume that the outputs may change somewhat unpredictably from the moment any input changes until the propagation delay time has passed.

In a circuit in which information is fed back, R1 and R2 in Fig.5 may be the same physical register. This does not change any of the arguments made here about timing. A counter circuit provides a typical example of fed-back data – the combinational logic takes the current count value, adds 1 to it and presents this to the input of the same register. At the clock edge the register loads its own current value plus 1, thus incrementing the count.

Delays and timing constraints

Again, with reference to Fig.5, we know that the after an active clock edge the outputs of register R1 will update after delay T_{DR} and the combinational logic will be outputting the final, stable value after a further delay of T_{DCL}. On the next active clock edge, the output of the combination

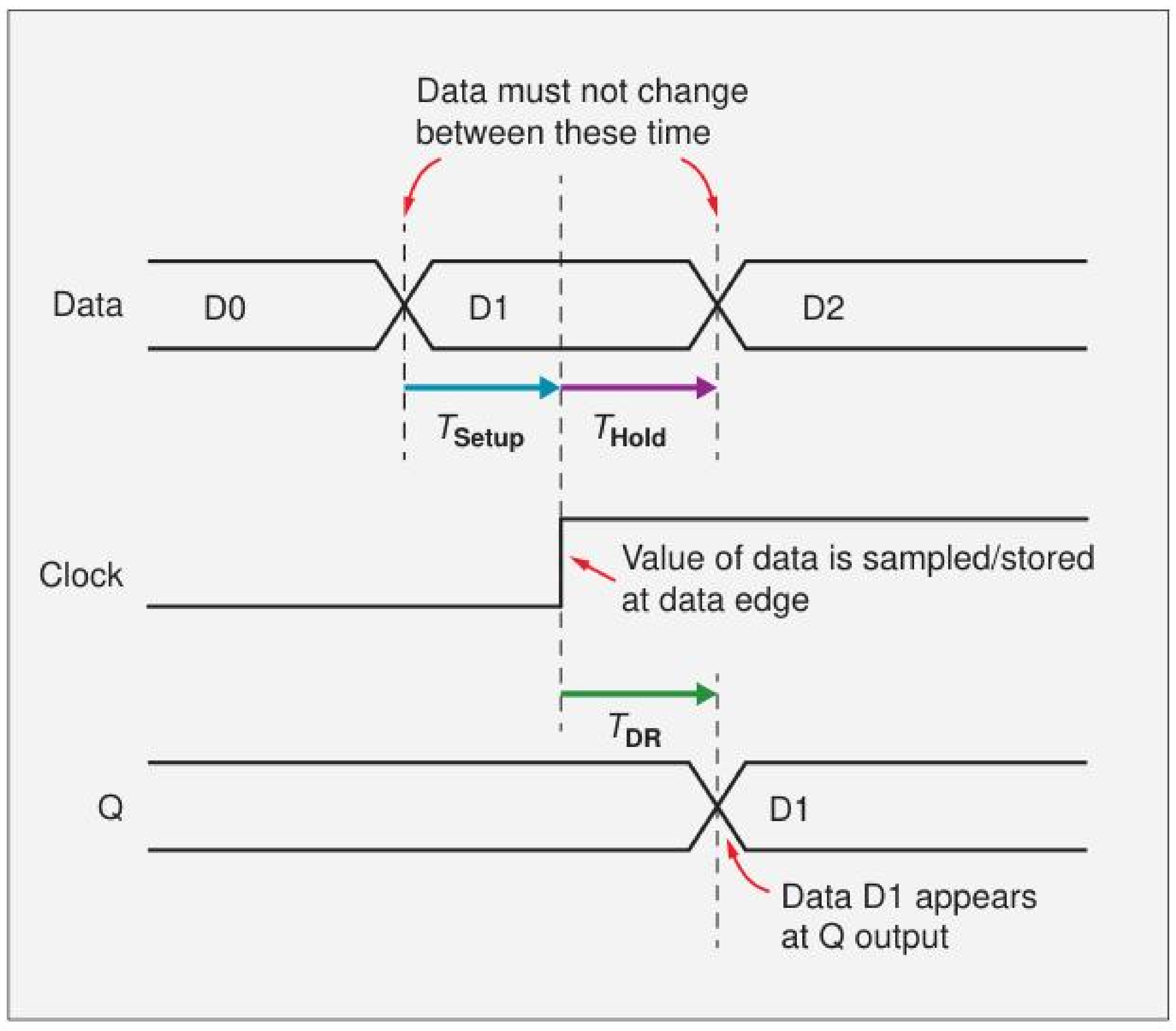

Fig.6. Definition of setup and hold times (D-type flip-flop).

logic will be loaded into register R2. It might seem that as long as the clock period is greater than T_{DR} + T_{DC}, R2 will load the correct value. In reality, the clock period has to be a bit longer than this because of the way R2 (or any register or flip-flop) responds to changes on its data input.

A clocked flip-flop only changes its output under the control of its clock input. Changes on the data input have no effect on the output if it is not clocked. However, data input changes do affect the internal circuitry. If the data changes, the flip-flop's internal circuitry takes time to settle in response to that change. If the clock is activated just after a data change, before the internal circuitry has settled, the flip-flop may not function correctly. It may load the wrong value or go metastable, potentially resulting in a much longer than normal delay before the output changes.

To help prevent these problems, flip-flops are specified in terms of the time that must pass after the data is changed before the active clock edge occurs – this is called the setup time (T_{Setup}). Similarly, the data must not change for a certain time after the active clock edge – this is the hold time (T_{hold}). Setup and hold times are illustrated in Fig.6. This timing diagram is for the purposes of defining timing parameters, it is not showing expected circuit operation. Normally, data changes would not be exactly on the setup and hold times as that would be too risky – some margin of error is needed.

Designers must ensure that circuits are configured so that the setup and hold times for all flips-flops are met under all operating conditions. For small simple circuits this may just be a matter of making sure the clock is not too fast, but in large complex designs timing analysis software tools (not the same thing as a simulator) can be used to find potential violations of these timing requirements. The values for the setup and hold times can be found in flip-flop datasheets.

Fig.7 shows the various delays associated with register-to-register transfer in a synchronous circuit. The minimum clock period must be greater than T_{DR} + T_{DC} + T_{Setup} to make sure that the data loaded into R2 is valid. The crosshatched part of R2's D input waveform (which is the combinational logic output) indicates the period when the combinational logic may be outputting intermediate values or glitches before is settles. This value must be guaranteed to settle before the setup time before the next active clock edge. If we find the value of T_{DR} + T_{DC} + T_{Setup} for every register-to-register transfer in the circuit then the slowest value (plus some margin for uncertainty) gives us the minimum clock period and hence maximum clock frequency for the circuit.

The discussion so far has simplified things a bit. In particular, the fact that the schematic in Fig.7 shows the clocks wired together and depicts a single clock waveform. In reality, the clock will arrive at every flip-flop at a slightly different time because each path the clock takes will have a slightly different delay. In small circuits this might not be noticeable, but it is a potential problem in larger circuits (such as on ICs) where the clock is not distributed simply by a wire to each flip-flop but goes through sets of buffers (a clock tree) and/or relative wiring distances may be significant. Variation in clock arrival times is called clock skew and needs to be taken into account when working out if timing violations may occur.

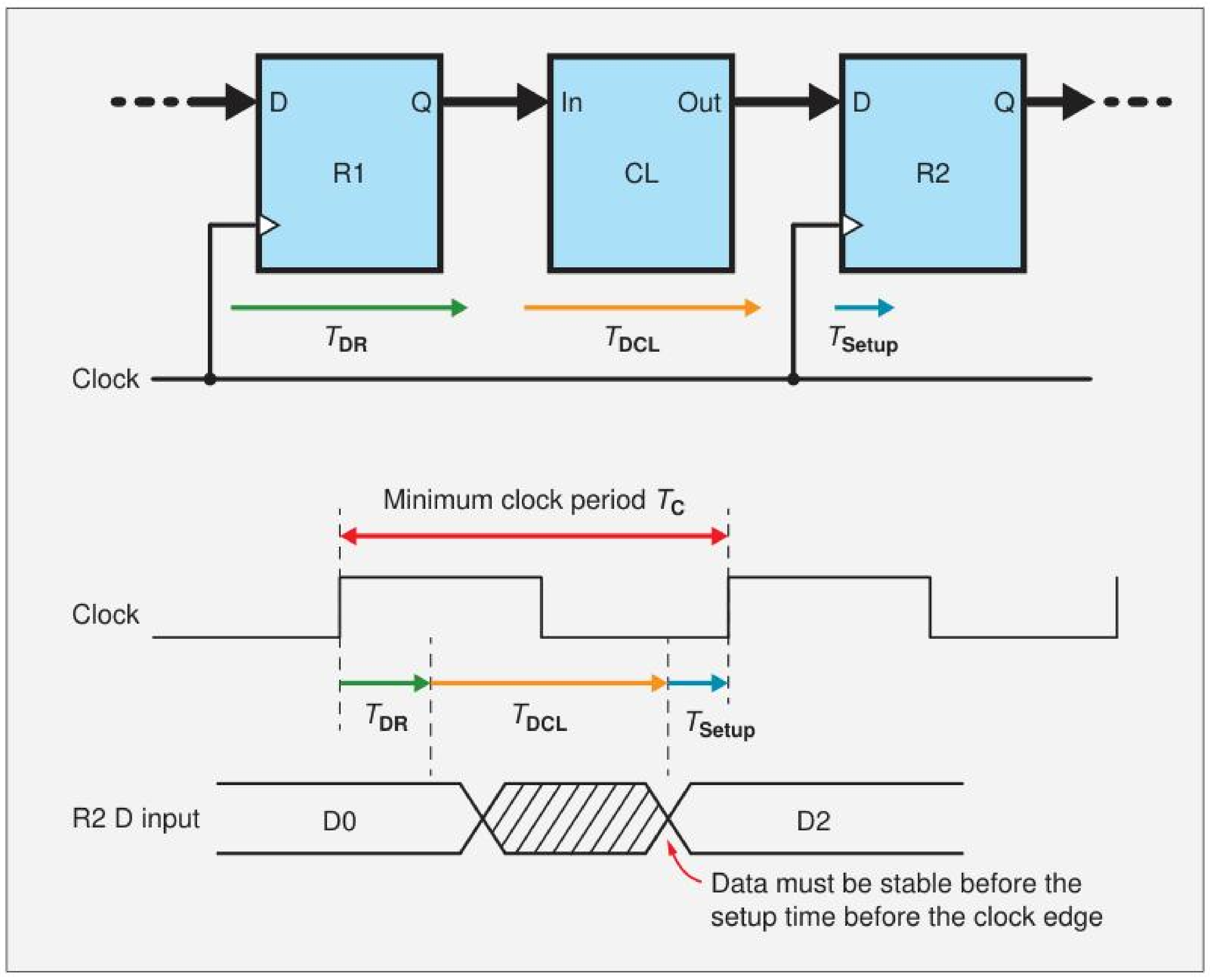

Fig.7. Detailed timing for register-to-register transfers.

Asynchronous signals and metastability

The previous discussion covers the basic requirements for preventing timing problems in synchronous circuits. If the requirements are met (with sufficient margin to account for any variability) then the circuit will not suffer timing problems – this is effectively guaranteed by design. The same does not apply when we have external asynchronous signals – they can change any time in the clock cycle, which means it is possible for them to change close enough to the active clock to cause timing violations (ie, within the 'must not change' time in Fig.6). Similarly, when signals cross clock domains, as outputs from stage 2 to stage 3 do in Fig.2, there is a possibility of timing violations. The situation is more complex than with asynchronous input because the clocks might have a specific relationship. If the clocks are derived from the same source and are powers of two different in frequency, then the situation is like the synchronous case and can be problem-free. More complex relationships may result in specific periodic violations. In cases where the clocks are independent and are likely to have some shift in relative phase and frequency with time, the situation may be similar to the asynchronous input case.

Last month, we looked at the structure of latches – the basic circuits which can store a single bit. The fundamental operation is shown in Fig.8 – when the clock (or SR inputs) changes state (so as to store a bit) a closed loop of two inverters is created that is isolated from the input(s). Two such data latches in series, controlled by opposite clock levels, are used to form the edge-triggered flip-flops that we have focused on this month. Under normal operation the loop stores a good logic 1 or 0 (on the Q output, with the other inverter outputting the opposite logic level). In this situation the loop is in a stable state and will stay as it is, storing the bit, until the clock/SR inputs update the stored value, or power is removed. However, we have to remember that the circuit is actually handling voltages – what happens if the voltage at the input to the loop is not a good logic 0 or 1 when the loop is formed?

If the loop happened to capture exactly equal voltages on the two inverter outputs, then it would be in a perfect state of balance and could, in theory, stay that way permanently – this is the

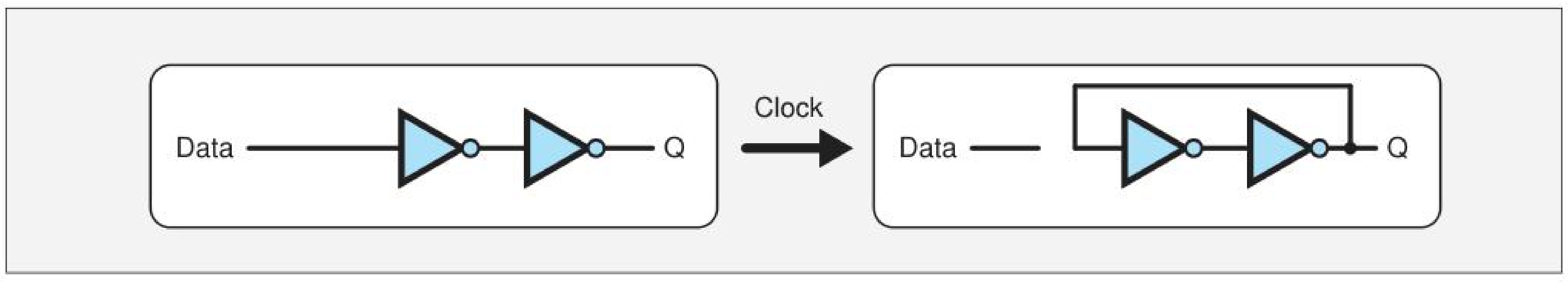

Fig.8. Fundamental operation of a latch circuit – the clock switches the circuit into closed-loop form to store the data. The mechanism by which this is achieved depends on the type of latch/flip-flop (see *Circuit Surgery*, February 2021).

metastable condition that we discussed in the context of the SR flip-flop last month. In last month's example the problem was caused by forcing an SR flip-flop to store a logic 1 on both inverter outputs. The design of data latches prevents this from happening, but voltages part way between good logic 0 and 1 can be stored by a data latch if the input voltage is changing between 0 and 1 when the loop is closed.

As discussed last month, the potentially infinite time in the metastable state will not happen in a real circuit – some difference or perturbation will result in the latch moving to one of its stable states. However, this may take much longer than the normal propagation delay of the latch.

We illustrated this last month with an LTspice transistor-level simulation of the latch loop. That example used the two-1s SR scenario, but a data latch storing a mid-supply voltage will behave in a similar way with a long delay. The loop circuit in Fig.8 will store an intermediate voltage if metastability occurs, but in a typical flip-flop the loop is not directly connected to the outputs – it may be the first of two latches and there are likely to be buffer gates at the output. This means that a metastable flip-flop may always output a good logic level but could exhibit behaviour such as very long delays or initially outputting one value and then changing.

The waveforms in Fig.9 show how a data latch may go metastable. There is a period of time as the data changes (metastability window, T_0) when clocking the latch will result in metastability. If metastability occurs then the latch will take an amount of time, called the 'resolution time' (T_R), before it returns to one of the stable states. For asynchronous inputs we have no control over the relative signal timing, so we cannot guarantee to prevent metastability. We have to deal with it in terms of probability. The probability of errors occurring in the circuit is related to the probability of a latch becoming metastable and the probability that it is then still metastable after the point at which this may cause an error. The probability of a latch becoming metastable is basically the proportion of the clock cycle taken by T_0, that is T_0/T_C. If we know the longest resolution time that can occur without causing a circuit failure, we can find the probability of this occurring – it is an exponential function related to the RC time constant of the latch loop. Such probability calculations can guide designers to reduce expected error rates to acceptable levels; for example, by adding synchroniser circuits. We will look at this in more detail in a future article.

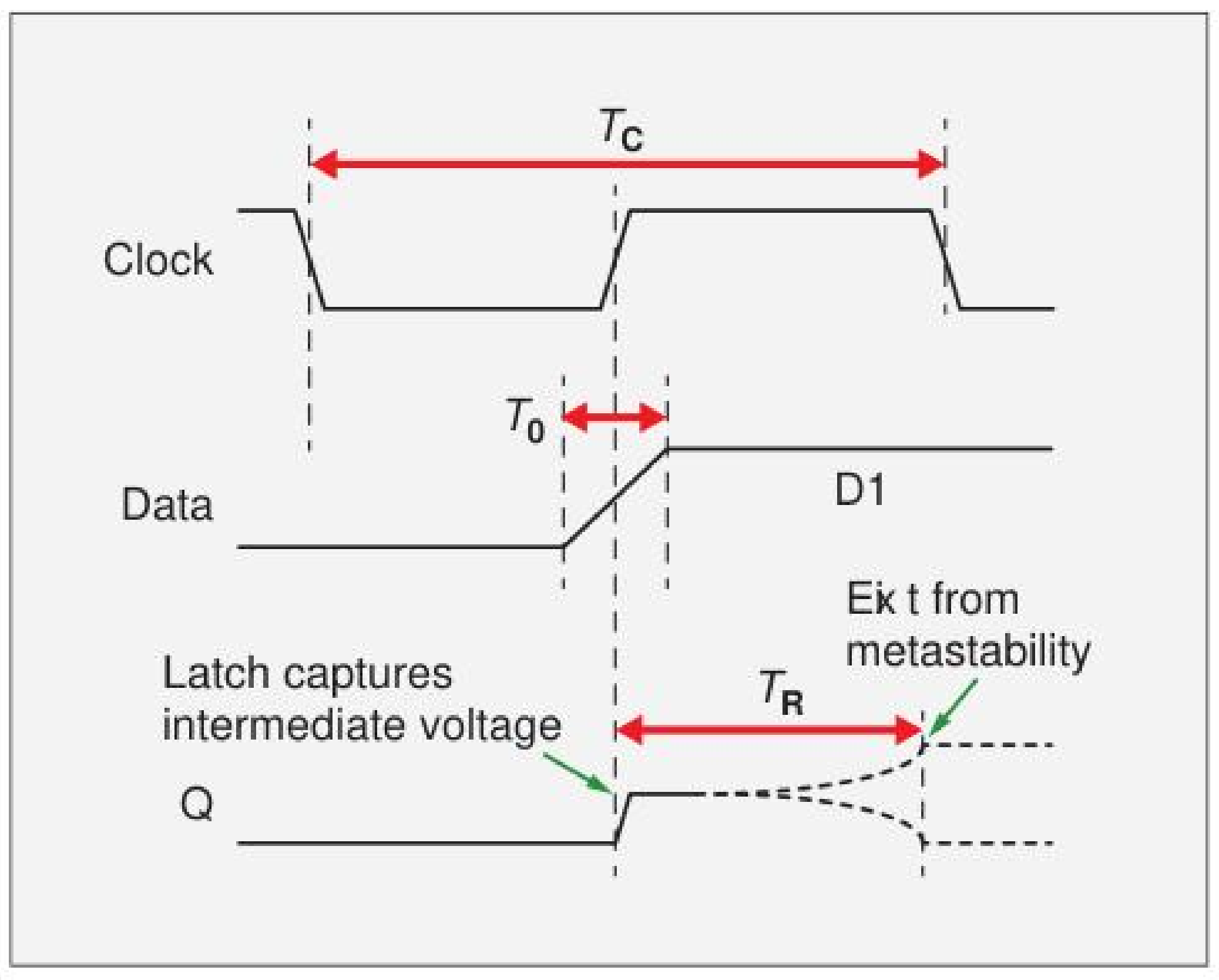

Fig.9. Latch metastability waveforms.

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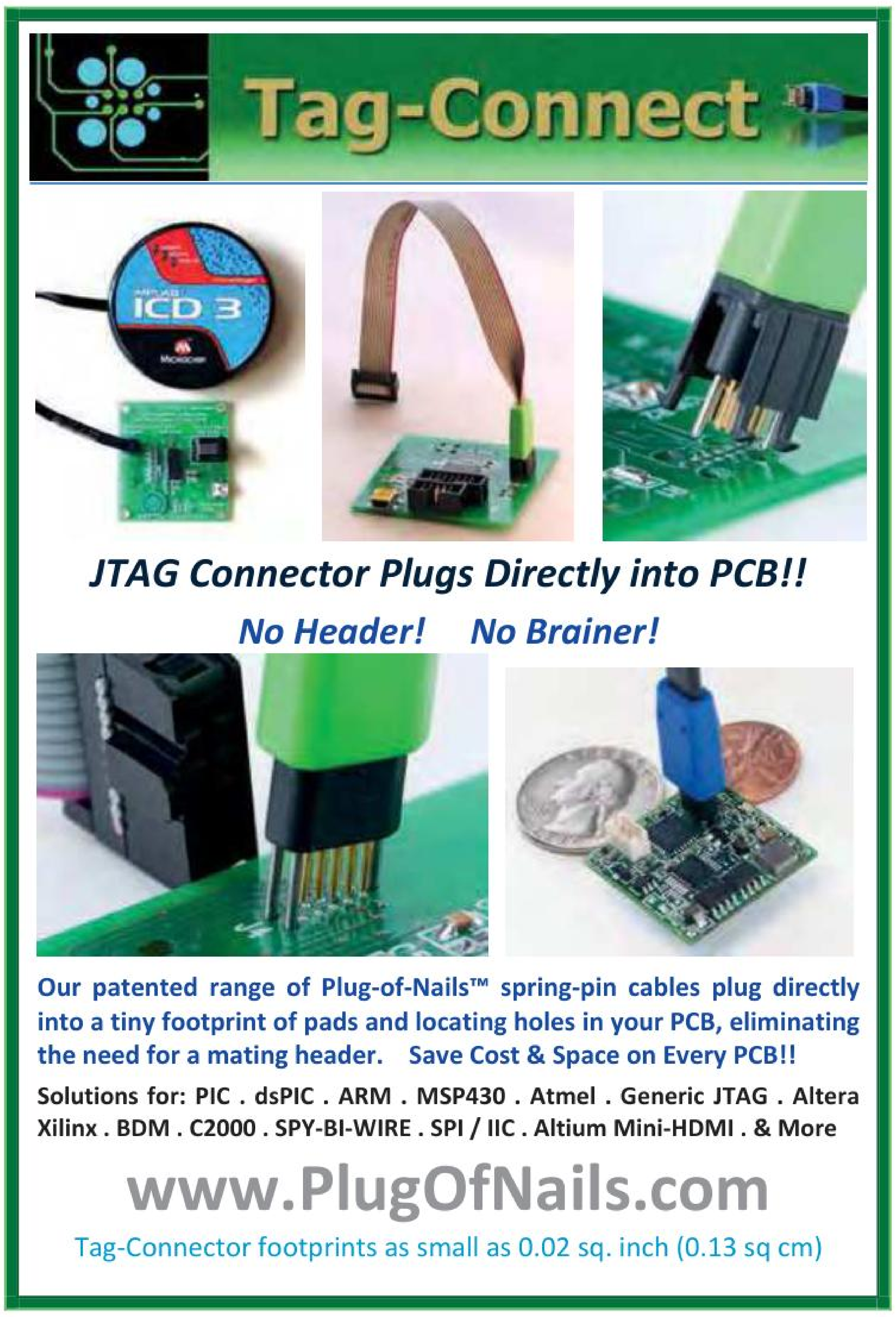
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Make it with Micromite

Phil Boyce – hands on with the mighty PIC-powered, BASIC microcontroller

Part 26: Having fun with a Micromite Plus

Last month, we discussed the main differences between the various versions of MMBASIC (Standard, Plus, and eXtreme). We also highlighted some of the different hardware modules that are available for use with these different versions of MMBASIC.

Throughout this series, we have used the Standard version of MMBASIC. There are two good reasons for this; first, it is the ideal starting point when learning about MMBASIC; and second, it is the only version of the firmware that loads onto an easy-to-solder DIP IC – ie, the 28-pin PIC that we used in the easy-to-build *Micromite Keyring Computer* (*MKC*).

Over this month, and next, we are going to work through a fun (and hopefully useful) project based around the more powerful Micromite Plus. Ultimately, this means that we have more I/O pins available than the *MKC*, which in turn means we can add hardware modules that have more than just the usual handful of pins. In this project we will be connecting to various hardware modules including a 64x32 RGB LED matrix display panel (see Fig.1), which requires 13 I/O pins.

Using Micromite Plus also means we have many new MMBASIC commands at our disposal; so, in this project we will be adding access to an SD card. We will show you how to write data to an SD card (which effectively means we will be creating a data logger), and also show you how to use a bitmap image that is stored on the SD card and display it on the 64x32 RGB panel.

In addition to the RGB panel and the SD card, we will also use a couple of items that we have previously used elsewhere in this series: an infrared (IR) receiver and a real-time clock module (RTC). By now, you will be familiar with using these on the *MKC*, and you will see just how easy it is to migrate them from the *MKC* for use with a Micromite Plus (it's the same MMBASIC commands, just different pin numbers).

Project overview

If you haven't already guessed from the introduction above (and the photo opposite), we are going to create a smart clock that uses an RGB LED matrix panel as the display (Fig.2). This is the type of panel that you see in electronic signage that is appearing everywhere. However, those signs typically use many tens or hundreds of panels to form the overall display, whereas we will just be using a single panel. Nevertheless, our single-panel display allows the time to be easily viewed from several metres away, making it extremely useful in larger rooms. It also looks fantastic!

In addition to the date and time, it also displays the current temperature. The temperature, date and time are all logged at regular intervals onto an SD card. The SD card can then be inserted into a computer and the data viewed in another application, such as a spreadsheet or graph. To add a fun element to this project, we will also incorporate the Mastermind game that we created earlier in the series (*Part 15*).

Incorporating an IR receiver means we are able to use an IR remote transmitter to control everything – so here we will use it to select a function from a simple menu in order to switch between the clock and the Mastermind game; and yes, you will be able to play the Mastermind game by remote control while sitting several meters away in your favourite chair. One other menu option will allow you to display a bitmap file stored on the SD card, albeit the resolution will be limited to the display's pixel resolution of 64x32.

Building blocks

This project will require the following main hardware items:

- Micromite Plus Explore 64 module
- 64x32 RGB LED panel
- RTC module
- IR receiver
- IR transmitter
- 5V PSU.

In addition, you will require a piece of stripboard to mount everything on, along with some wire-links, and various pin-strips, sockets and a couple of screw terminals. You will also need a micro-SD card to

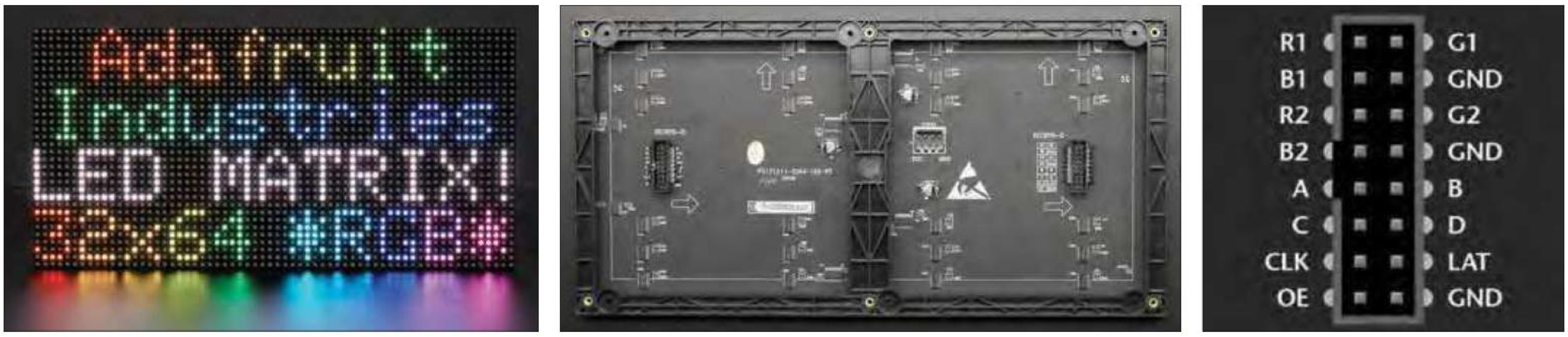

Fig.1. A typical 64x32 RGB LED matrix panel (LR): a) front, b) rear, c) connection to it is via a 2x8 connector (ribbon cable) with the pinout as shown.

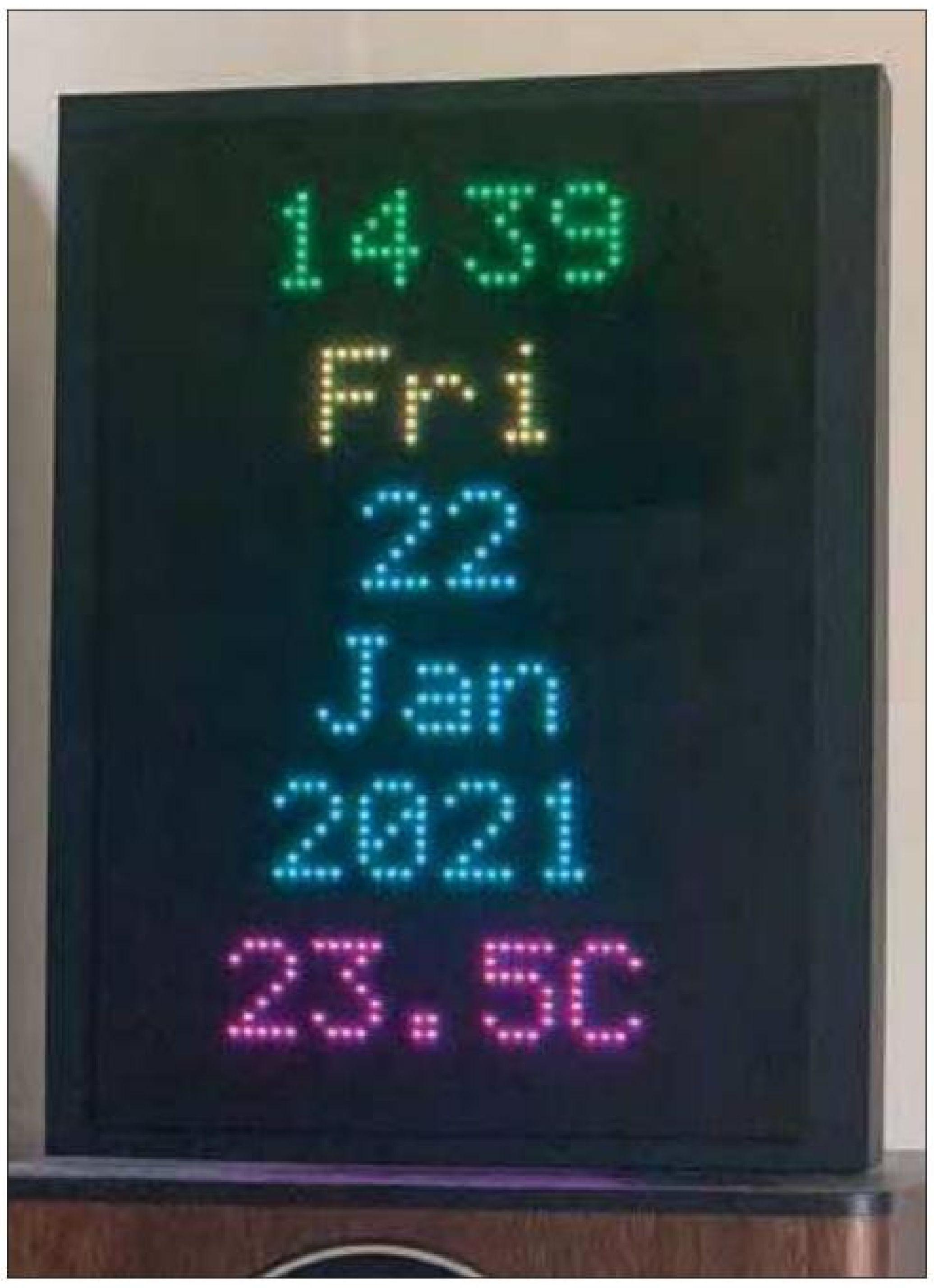

Fig.2. This fun project looks amazing when housed in a photo frame that uses a dark, LED-friendly front panel.

store the temperature data and any 64x32 bitmap image files.

Optionally, you can add an HC-05 Bluetooth module (as discussed in *Part 14*), allowing you to remotely access the Micromite Plus and make code changes from the comfort of your armchair!

You may have noticed that there is no temperature sensor listed above – so how can it display the temperature? The answer is that the RTC module is based on the DS3231 chip, and this has a built-in temperature sensor, so no separate sensor is required. Access to the temperature value within the RTC is via software, more on that next month – this month, we will just focus on hardware. First, let's discuss how to source the above items.

Micromite Plus Explore 64 module

Various versions of the Explore 64 module (also known as the E64) have been released over the last few years. However, they all comprise a 64-pin PIC pre-programmed with MMBASIC Plus, and they all have an onboard microSD socket. The E64 has two rows of downward-facing pins that allow it to be easily plugged into a breadboard, or alternatively plugged into your own custom-board via two rows of sockets (as in this project). All versions of the E64 have the same footprint, and pinout sequence for all of the I/O pins and power pins. Hence, any version can be use in this project. It's available from **micromite.org** for just £29.95 plus shipping. For further technical details, including a circuit diagram of the original E64, please visit: **https://geoffg.net/Explore64.html**

64x32 RGB LED panel

The RGB panel is the focus of this project and they're available from many places. However, the cost varies considerably, from about £20, up to just over £100. Do not let this put you off; an online search for 'RGB LED Matrix Panel 64x32' will lead you to places where you pay the lower end of this price range. You will see references to the 'pitch', which essentially means the distance in mm between the pixel centres. The pitch is often referred to as the 'P' number, so an 'LED matrix 64x32 P4' means the pixels are 4mm apart. Multiply this by 64 (and add a bit for the edges) and this gives an approximation to the physical length of the panel (ie, a bit longer than 25.6cm). So, the higher the P number, the bigger the panel. Typical P numbers are: 2.5, 3, 4, 5, 6, 8 and 10. The panel shown in the photo (Fig.2) is a P3, which is nice and compact. Two warnings when choosing a panel; first, do ensure it is a 64x32 (and do not go for a smaller or larger one as the display driver won't work correctly); and second, do check it has a 2x8 interface with pins labelled as in Fig.1. If the pin names are the same, but in a different sequence, then it will be fine to use, but you will need to modify the stripboard wire-links accordingly. It is far easier to just find a matching pinout. In the past I have used one from here (no affiliation): **http://bit.ly/pe-mar21-miwm1**

RTC module

This is the same small DS3231 RTC module as used previously in this series for various other projects. It comes with a pre-soldered 5-way socket. You can search online for 'RPi GPIO RTC' to find many places from which to source this module cheaply. One example of a reliable UK seller (and no affiliation) is: **http://bit.ly/pe-mar21-miwm2**

IR Receiver and Transmitter

This project uses the usual TSOP4840 (or TSOP4838) IR receiver that we have used several times in this series. So, you probably already have one; however, if not, they are readily available online. Likewise, with the transmitter, we have used two different types in this series; a smaller one for the *Electronic Dice* (*Part 5*), and a 44-button transmitter for the *Mood Light* (*Part 13*). Note that literally any IR Transmitter can be used providing it meets either of the two common IR protocols (NEC or Sony). All we need to do is alter the project's program code slightly in order to decipher the various IR codes from any button presses. This will be covered next month.

5V PSU

The RGB panel has a total of 2048 pixels (ie, 64x32). Each pixel comprises three LEDs (R, G, B), meaning that there are 6144 LEDs in total. Taking into account that each LED requires circa 15mA, this equates to an immense amount of power. However, the RGB panel's internal circuitry multiplexes the LEDs, which essentially means that the potential number of LEDs turned on at any one moment in time is limited to a finite number, *much lower* than 6144. The result is that multiplexing reduces the maximum power required significantly. Even so, a decent 5V power supply must be used for this project, and you certainly don't want to drive it from your computer's USB port (which is typically limited to a maximum of 500mA). We recommend an official Raspberry Pi 4 Power Supply, available online for around £7.50. They can reliably supply 5.1V at up to 3A. They come with a hardwired USB-C connector on the end, but we can simply cut this off to expose the 0V and 5.1V wires which are inserted into a 2-way screw terminal. Alternatively, you can use a redundant tablet charger which should be able to supply 2.1A. Otherwise just use any 5V power supply with a minimum delivery of 2A.

SD card

The E64 works with any micro-SD card that has a capacity between 8GB and 64GB. There is no need to buy the latest high-specification card, but we do recommend using a branded one. For example, a 16GB SanDisk card should cost around £8.

Circuit diagram

As with all our circuits in this series, it is just a matter of connecting the relevant pins from the various items to the correct I/O pins on the Micromite; and then supplying power to each item. In this project, we need to connect the MM+ to the RGB panel (13 I/O), the RTC (2 I/O), and the IR receiver (1 I/O). All the pin numbers used in this project are shown in Fig.3.

The RGB panel is driven by a display driver that effectively 'bit-bangs' the required signals over 13 standard I/O pins. The RTC communicates via I^{2}C and hence is connected to the E64's I^{2}C Data and Clock pins (pins 43 and 44 respectively); and the IR receiver connects to the E64's IR input pin (pin 51). All three items, including the E64, require a 5V supply, and this is supplied via the external PSU described above.

Connectors are not shown in Fig.3; however, they are discussed below in the construction section.

Assembly

Apart from the RGB panel and the PSU, everything is assembled onto a piece of stripboard which is 36 tracks wide, with 26 holes in each track. The RGB panel is then attached via a short ribbon cable (supplied with the RGB panel); and the 5V PSU is attached via a 2-way screw-terminal. Fig.4 shows the stripboard layout which includes the wire links, track cuts, and component (or rather connector) placements.

To begin with, cut the stripboard to size, and then make the 11 'regular' track cuts

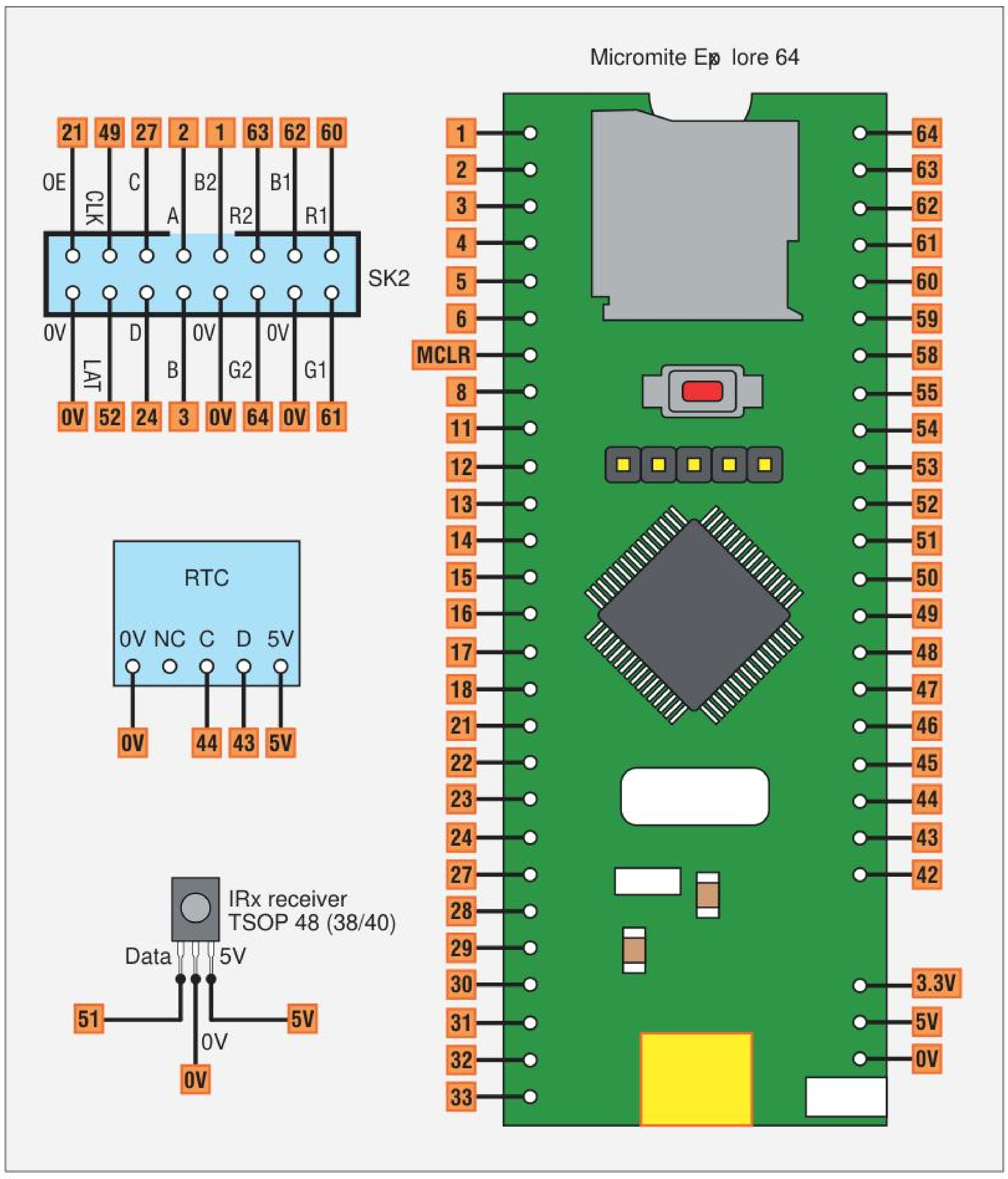
Micromite Explore 64
21 49 27 2 1 63 62 60
OE C B2 B1
CLK A R2 R1
SK2
0V D 0V 0V
LAT B G2 G1
0V 52 24 3 0V 64 0V 61
RTC
0V NC C D 5V
0V 44 43 5V
IRx receiver
TSOP 48 (38/40)
Data 5V
51 0V 5V
0V
1 2 3 4 5 6 MCLR 8 11 12 13 14 15 16 17 18 21 22 23 24 27 28 29 30 31 32 33
64 63 62 61 60 59 58 55 54 53 52 51 50 49 48 47 46 45 44 43 42
3.3V 5V 0V

Fig.3. (left) This project comprises an E64, RGB panel, RTC module and IR receiver.

shown in Fig.4. There are also eight additional track cuts that need extra care as they are made mid-way between rows P and Q in tracks 1-8 (marked in red in Fig.4). Ensure that all 19 track-cuts fully extend the width of the track (either visually, or ideally by using a continuity tester). Next, use a pencil to mark out the end positions of the 25 wire links, recheck the markings, then go ahead and install them. Two 2-way screw terminals (SK1 and SK3) may require the stripboard holes to be made slightly bigger – if so, use an appropriately sized drill bit.

SK2 is a shrouded socket to which the RGB panel connects via an IDC ribbon cable connector. This is 8x2 in size, and if you don't have one available, then you can use two rows of 8-way header pins instead. However, you will then need to take great care when you attach the RGB panel's ribbon cable connector to ensure it is inserted the correct way round.

JS1 is a 3-way socket, allowing the IR receiver to be plugged in (and removed if needed elsewhere). Alternatively, you can solder the IR receiver directly into this position, avoiding the need for JS1. Do ensure that the IR receiver's 'bump' is facing outwards and away from the stripboard.

JP1 is a 5-pin header, to which the RTC module is attached, and JS4 is a 6-way socket into which the optional HC-05 Bluetooth module can be inserted. Apart from JS2 and JS3, now mount all of the screw terminals, header pins and sockets as required. When it comes to the 'long sockets' JS2 and JS3, extra attention is required. Essentially, they can be made up of several shorter header sockets that are butted up together to create the 27 positions. However, it is essential that you pull out the contacts from the socket's housing for all unused pins. This is easily achieved with a pair of nose pliers or side cutters. To clarify, you should be left with contacts only in the positions marked in Fig.4 (ie, in the top row: G10-14, G16, G20-21, G23, G28-29, G34-35; and the bottom row: P10-12, P15, P26, P29-30). If you do not carry out this step, then you will certainly run the risk of permanent damage to the E64. Once all the redundant contacts have been removed, solder in these sockets.

As always, do a thorough visual check when you have finished assembly. Do not be tempted to insert any modules yet as they will be added gradually next month during the testing process.

Next month

After the hardware assembly, next month we will test it bit-by-bit, configuring the Micromite Plus as we go. Then, to finish, we will show you how to make everything come together by installing the appropriate program code. In the meantime, why not take a look at the *Micromite Plus User Manual* (available for download from the March 2021 page of the *PE* website). and explore some of the many additional features that your new hardware provides. Until then, have fun!

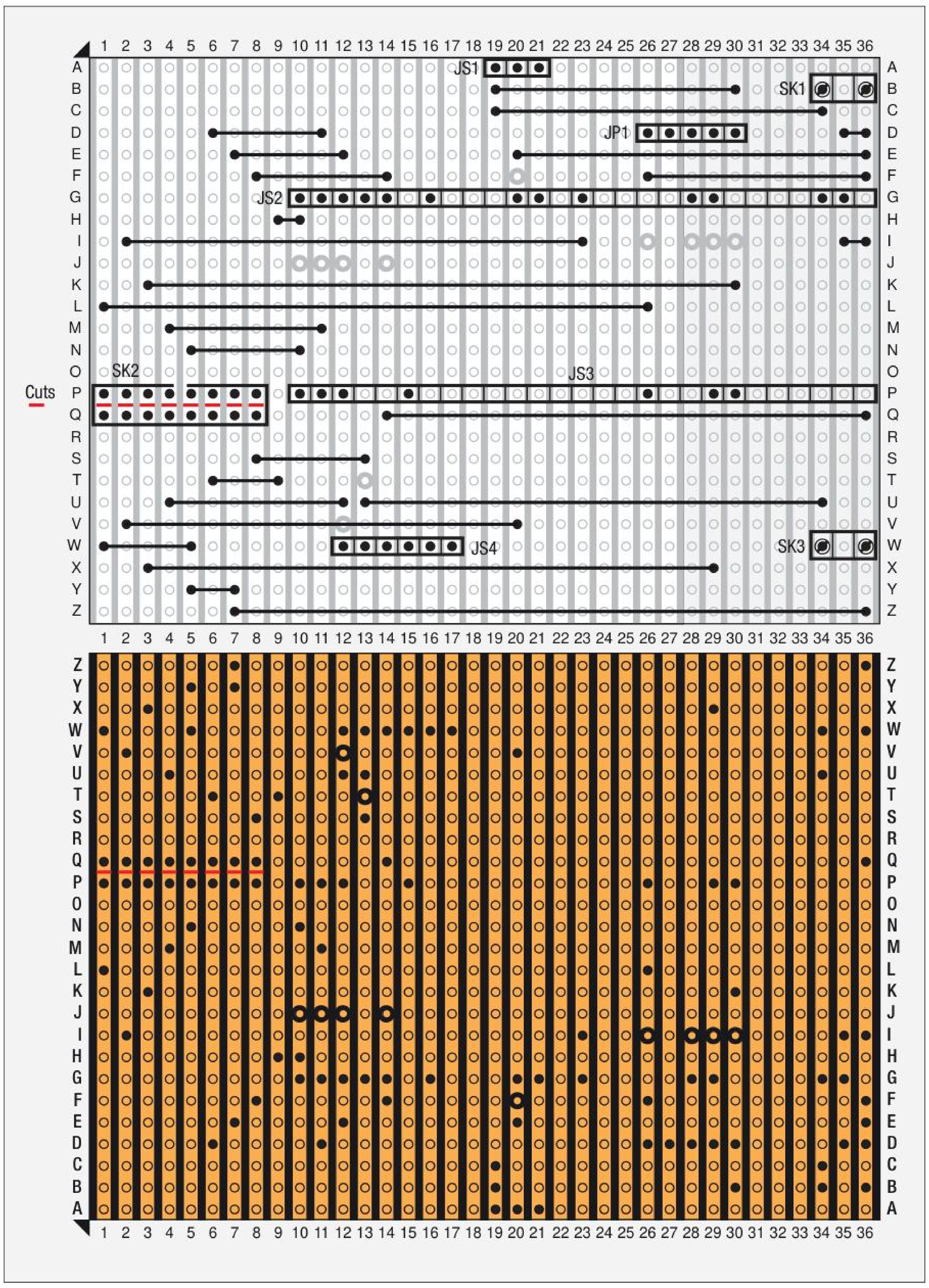
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36
A B C D E F G H I J K L M N O P Q R S T U V W X Y Z
JS1
SK1
JP1
JS2
SK2
JS3
Cuts
JS4
SK3
Z Y X W V U T S R Q P O N M L K J I H G F E D C B A

Fig.4. (left) The top and bottom sides of the stripboard showing the position of all the required track cuts, wire links, and connectors.

Questions? Please email Phil at:
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PIC n' Mix

Mike Hibbett's column for PIC project enlightenment and related topics

Part 4: PIC18F Development Board

In the last PIC n' Mix article (January 2021), we discussed the design requirements for a PIC18F development board, creating enough detail that we believed this month's task of designing the schematic and layout of the board would be simple. Now, let's put that to the test.

Our goal this month is to take the high-level schematic shown in Fig.1 and create the design for a PCB that we can have manufactured quickly and cheaply by a PCB supplier. We will go with JLCPCB based in China for this board, to test how easy their service is to use compared to our favourite supplier PCBWay.

We will be designing this board in EagleCAD, which is now part of AutoDesk's Fusion 360 product offering. The software is still available for free to hobbyists and small companies; and it has been our default PCB design tool for over a decade. We're using it out of familiarity, but completely free CAD programs such as KiCAD would be just as suitable. Due to its continual development KiCAD has become a viable alternative to commercial programs, and we will one day move over to it. Not this month though!

PCB design process

The CAD design process for our board will follow a fairly standard process. We have already chosen our component technology – through hole, not surface mount – and thanks to the relatively slow speeds of the signals on the board, we know that a simple double-sided board, with components mounted on one side, will be acceptable. We don't have any design constraints on the size of the PCB so we shouldn't need complicated 'tricks' like components mounted on both sides, or a four-layer PCB to allow the components to be positioned close together.

Space between components will be desirable for ease of assembly and access to pins/leads with test clips or probes. The final dimensions of the board will only become clear once we have placed our components roughly in their positions. We start with a large outline for the board, iteratively place components, reduce the board dimensions and then move components again until the right balance of board size and component proximity is achieved. Component placement is a personal choice, as there are no specific design constraints, but it seems sensible to have power and the main I/O signals at the edge of the board and the CPU in the middle.

Library of parts

That's the process but we're getting a little ahead of ourselves. First, we need to create a schematic, and for that we need a library of components to choose from. There is a 'chicken and egg' situation here; while EagleCAD (in common with all CAD programs) comes with an extensive library of components, it is reasonable to expect that some of our desired components may not be present – requiring us to design the footprint, mechanical layout and schematic symbol for these missing parts.

Creating library parts can be a tedious task, but a search on the Internet can often reveal downloadable libraries created by companies and other hobbyists. A simple Google search, such as 'EagleCAD DC Barrel socket library', can often be successful, but also note that libraries for many components are made available by some component suppliers such as Farnell, RS Components, Sparkfun and Adafruit.

The process for creating a component library is complex as there are additional features that must be drawn, including the location of solder paste, silkscreen and solder mask. The mechanical dimensions must be accurate too, or you risk the component not fitting. So, finding and reusing a pre-existing library is highly desirable, and is one of the reasons we have stayed with EagleCAD over the years – it seems to be the most popular CAD program for downloadable libraries, although KiCAD is growing in popularity.

Our preferred approach when an existing library cannot be found is to pick an existing component that uses the same physical package, copy it and modify it to the requirements of the new part. It's quite possible we may need to do that for our choice of processor, at least.

Let's begin the journey by going back to our high-level schematic, shown in Fig.1, attacking each circuit subsystem in turn and identifying the required components. Once done, we can simply 'bolt' them together on the schematic, with perhaps an extra decoupling capacitor thrown in for good measure.

Power supply

We have already decided that we want to be able to support both 3.3V and 5V as the system voltage, since some sensors and servos run at the higher voltage. This could be achieved using two voltage regulators with a 0.1-inch jumper header to select between them, but to save cost we went with the LM317 – an adjustable output voltage linear regulator. This is a very simple low-cost regulator, available in easy-to-solder packages. It's not an efficient regulator and will waste some energy as heat, but since we are not targeting battery power for this board that's not much of an issue. Although the datasheet is difficult to read (there are many uses for this regulator) it boils down to the circuit shown in Fig.2, with decoupling capacitors on the input and output power pins. We replace the single resistor R2 with two resistors, and a jumper shorting one of them sets the desired output voltage. The jumper allows the 'R2' resistor to be switched between 390Ω and 720Ω, and a resistance of 240Ω for R1 giving the desired voltage.

To connect power to the board we will allow for two options – a standard 'barrel jack' connector, common on mains 'brick' power supplies, and 0.1-inch header pins for quick wire connection. The barrel jack presents an interesting problem with the PCB design, which we will pick up on later.

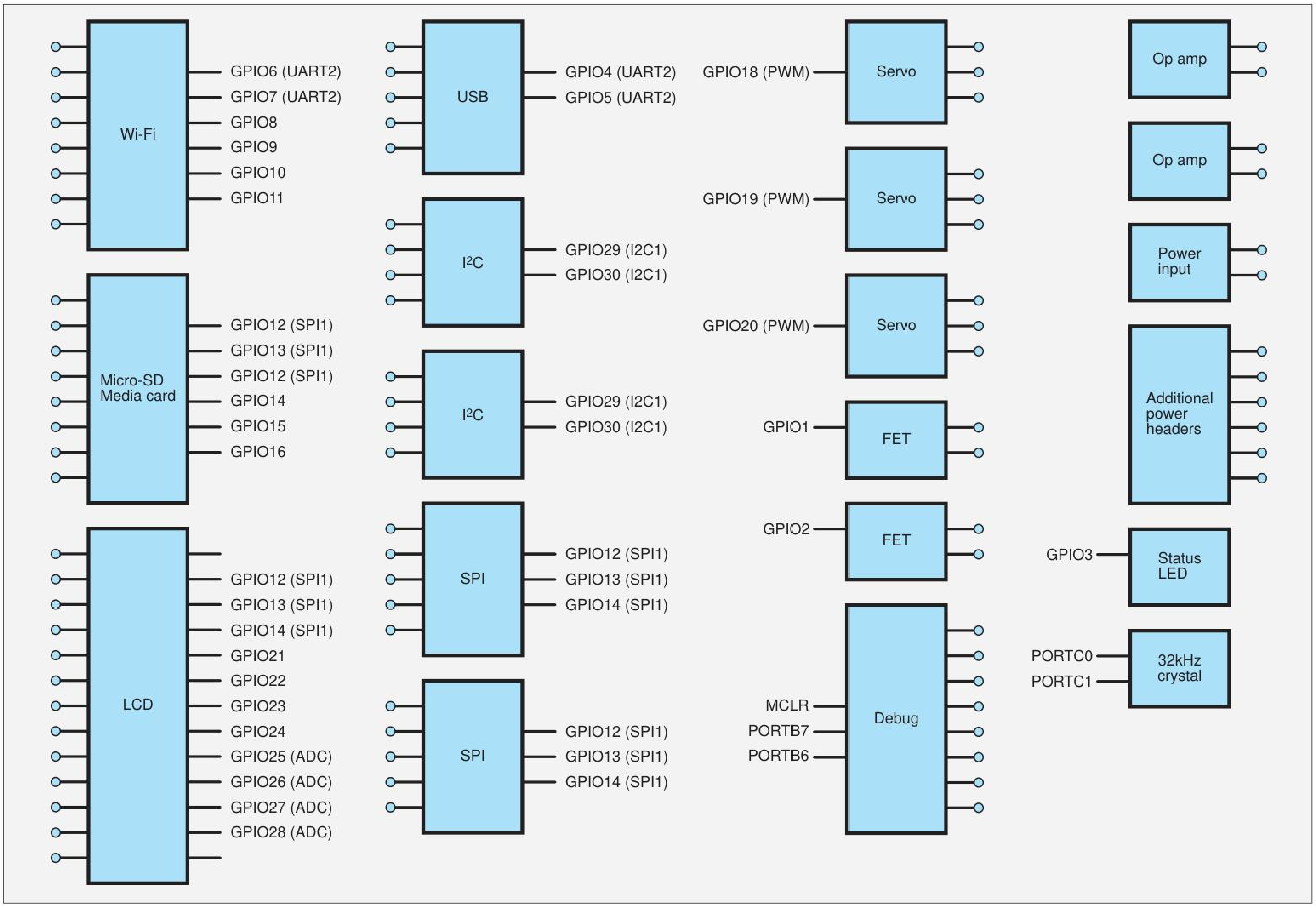

Wi-Fi
GPIO6 (UART2)
GPIO7 (UART2)
GPIO8
GPIO9
GPIO10
GPIO11
Micro-SD Media card
GPIO12 (SPI1)
GPIO13 (SPI1)
GPIO12 (SPI1)
GPIO14
GPIO15
GPIO16
LCD
GPIO12 (SPI1)
GPIO13 (SPI1)
GPIO14 (SPI1)
GPIO21
GPIO22
GPIO23
GPIO24
GPIO25 (ADC)
GPIO26 (ADC)
GPIO27 (ADC)
GPIO28 (ADC)
USB
GPIO4 (UART2)
GPIO5 (UART2)
I²C
GPIO29 (I2C1)
GPIO30 (I2C1)
I²C
GPIO29 (I2C1)
GPIO30 (I2C1)
SPI
GPIO12 (SPI1)
GPIO13 (SPI1)
GPIO14 (SPI1)
SPI
GPIO12 (SPI1)
GPIO13 (SPI1)
GPIO14 (SPI1)
GPIO18 (PWM)
Servo
GPIO19 (PWM)
Servo
GPIO20 (PWM)
Servo
GPIO1
FET
GPIO2
FET
MCLR
PORTB7
PORTB6
Debug
Op amp
Op amp
Power input
Additional power headers
GPIO3
Status LED
PORTC0
PORTC1
32kHz crystal

Fig.1. Our *PIC Development Board's* high-level schematic (see *PIC n' Mix*, January 2021).

USB interconnection

Next, we look at the USB serial interface, which will be based on the MCP2221A IC from Microchip. Despite the complexity of what it does, the support circuitry for this device, as shown in the data sheet, is very simple – just two capacitors – see Fig.3. We copy this directly.

For the physical connection, USB connectors are only available in surface-mount format. They are very challenging to solder so we will use an off-the-shelf USB connector breakout board that provides an easy-to-solder 0.1-inch header interface, which we will connect to with a plug and socket arrangement. If you are looking to save costs, you could take a standard USB cable, cut the end off and solder the wires directly to header pins.

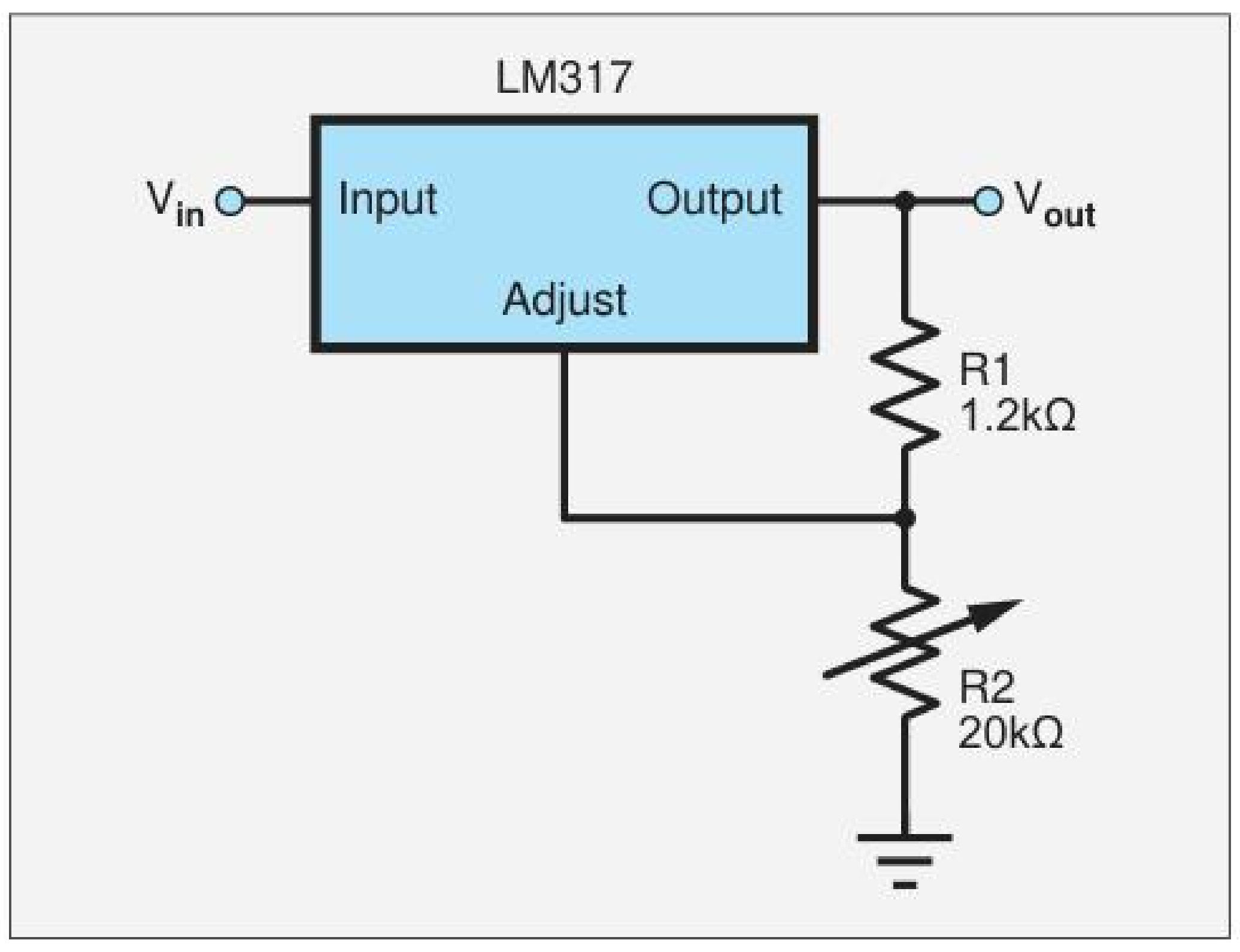

LM317
V_{in}
Input
Output
V_{out}
Adjust
R1
1.2kΩ
R2
20kΩ

Fig.2. Power supply schematic (from Microchip datasheet LM317).

FET subsystem

We will tackle the FETs next. In the previous article we did not go into the details of how the FETs would be configured, which does leave some ambiguity. Will we use a high-side or low-side FET switch? By this we mean, will the FET be tied to the positive supply line, or the ground?

We will take the simpler approach, which is to place the FET switch in the ground supply line. This has two benefits: the circuit will require N-channel FETs, which tend to have a lower resistance between drain and source resulting in a smaller-package FET that can sink a relatively large amount of current for its size. Second, the gate 'on' voltage level only needs to be a few volts above ground, so we can drive it directly from the CPU, reducing component count.

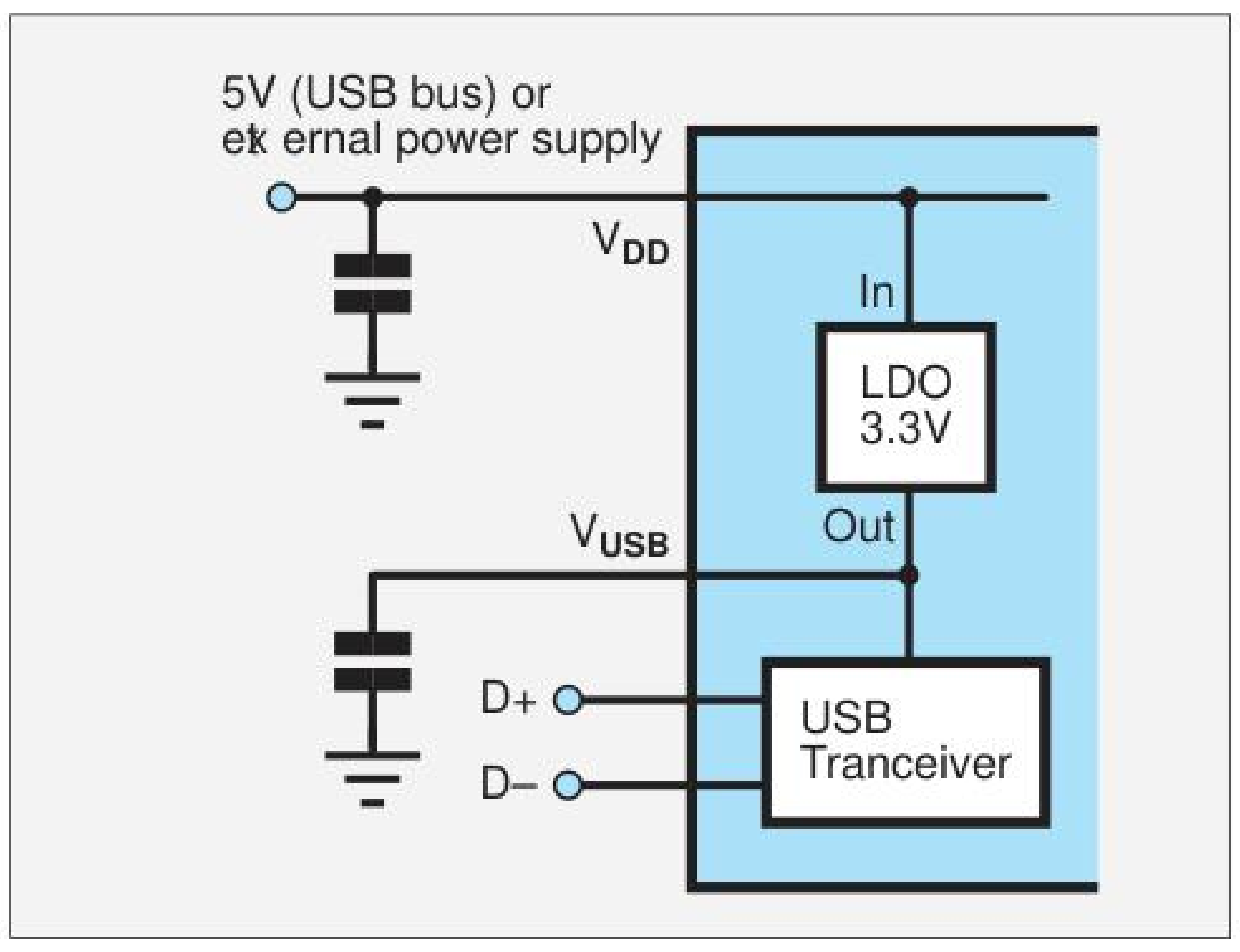

5V (USB bus) or
external power supply
V_{DD}
In
LDO
3.3V
V_{USB}
Out
D+
D–
USB
Tranceiver

Fig.3 USB interface (from datasheet Microchip CP2221A).

Now that choice has been made, our design decisions become:

- What current do we want to be able to support?
- What package are we willing to tolerate for the FET (TO92 or the larger TO220)?
- Will the FET switch on with a digital signal from the microcontroller?

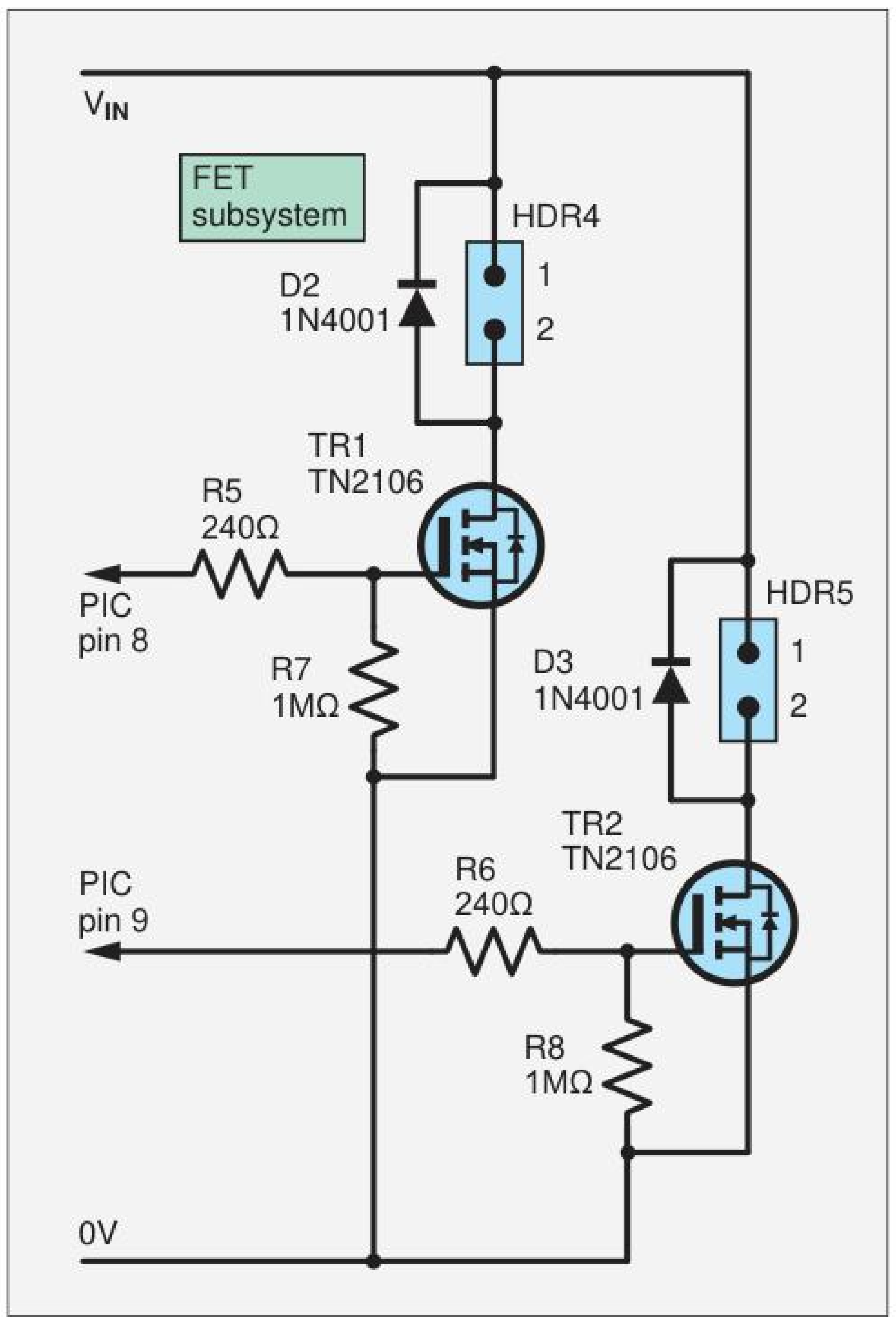

V_{IN}
FET subsystem
HDR4
1
2
D2
1N4001
TR1
TN2106
R5
240Ω
PIC
pin 8
R7
1MΩ
D3
1N4001
HDR5
1
2
TR2
TN2106
R6
240Ω
PIC
pin 9
R8
1MΩ
0V

Fig.4. FET subsystem (the power comes directly from the supply, not the regulator).

We decide to go with a TO92-packaged TN2106N3-G, from Microchip. It has a very low resistance, 0.35Ω; will turn on with a gate voltage of 2.2V; and can sink 1.2A continuously. This seems a reasonable compromise; FETs in the TO220 package can sink tens of amps, but supporting such a current drain would have introduced challenges to the rest of the PCB design.

The basic building blocks for our FET drive circuit (we decided to add two such circuits in our design) are shown in Fig.4. This is a simple and standard configuration for low-side N-channel FETs. The resistor to ground is there to ensure that the FET does not turn on accidentally, should the I/O pin driving it be set as an input (not a problem if no load is connected to the FET, but could be problematic if one were.) The series resistor may come as a surprise – The gate input resistance on a FET is extremely high – in the order of 100MΩ. What possible effect could a 220Ω resistor have?

The gate of a FET has a relatively high capacitance, and there can be a brief but high current surge as the gate voltage rises and charges the gate. A low-value series resistor is a simple and low-cost method to reduce that current peak down to a few tens of milliamps. As we do not intend to be switching the FET on and off at high frequencies, the resistor is an appropriate solution. If we were designing a switching power supply with a gate-signal switching speed of over 100kHz, then a dedicated high-current driver circuit would have been required. On a development board like this, the value of that series resistor is fairly unimportant, so we may change the value later to a common value used elsewhere, to reduce the number of component variants.

As a final point, you can see in the FET circuit that we've added a reverse-biased diode across the header. This is an optional component, designed to cater for any inductive loads you might be switching (such as motors or relays.) These loads generate a large back-EMF voltage spike when power is turned off, and the diode will conduct this energy safely to ground. The FETs have a 'body' diode within their construction, but if the inductive load is large (or you are passing a large current) a discrete diode will provide a more powerful sink for this voltage spike, preventing damage to the FET and the microcontroller.

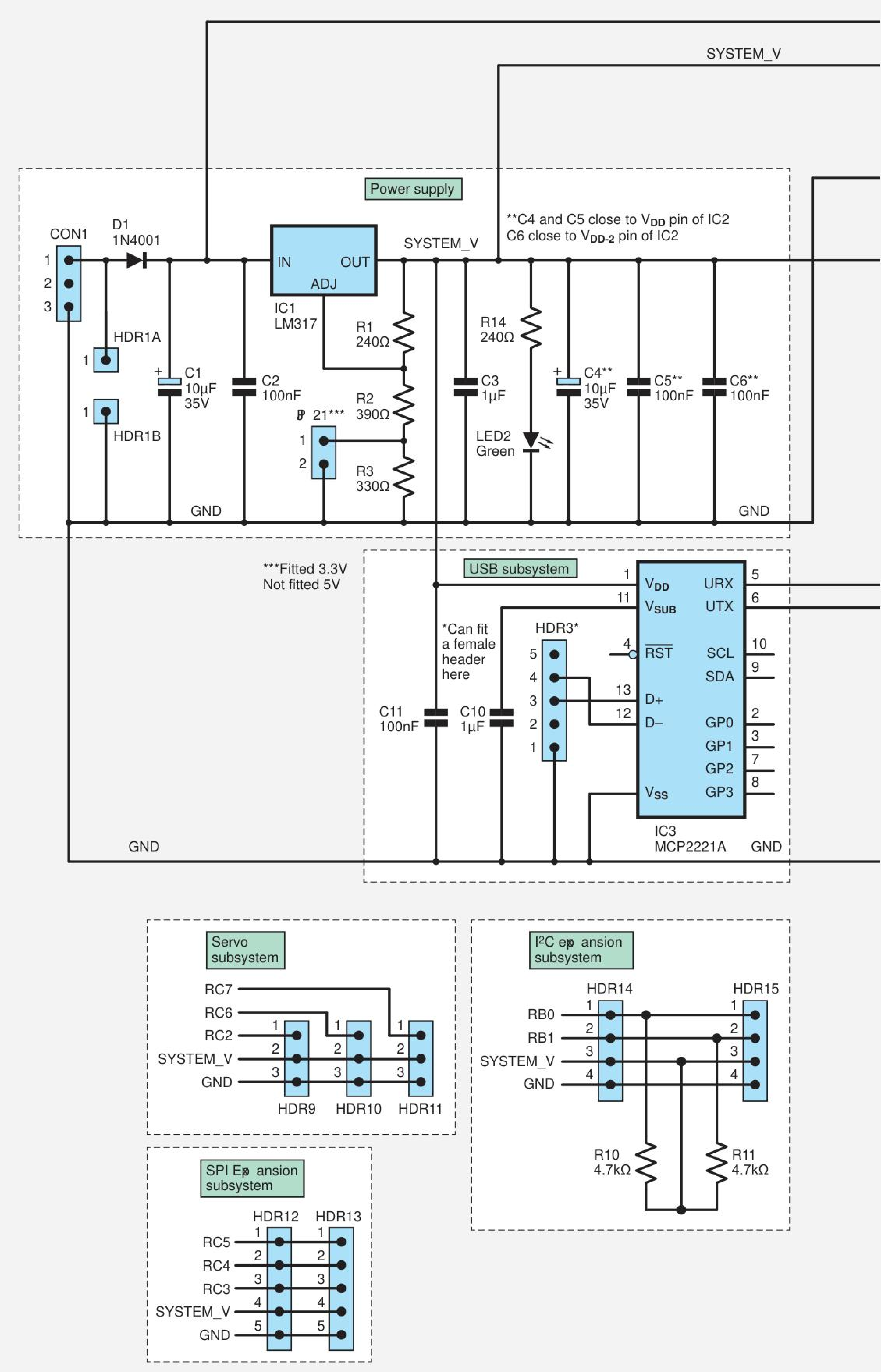

SYSTEM_V
Power supply
**C4 and C5 close to V_{DD} pin of IC2
C6 close to V_{DD-2} pin of IC2
CON1
1
2
3
D1
1N4001
IN
OUT
ADJ
IC1
LM317
SYSTEM_V
HDR1A
HDR1B
C1
10µF
35V
C2
100nF
R1
240Ω
R2
390Ω
R3
330Ω
P 21***
R14
240Ω
C3
1µF
LED2
Green
C4**
10µF
35V
C5**
100nF
C6**
100nF
GND
GND
***Fitted 3.3V
Not fitted 5V
USB subsystem
*Can fit
a female
header
here
HDR3*
C11
100nF
C10
1µF
V_{DD}
V_{SUB}
URX
UTX
RST
SCL
SDA
D+
D–
GP0
GP1
GP2
GP3
V_{SS}
IC3
MCP2221A
GND
GND
Servo
subsystem
RC7
RC6
RC2
SYSTEM_V
GND
HDR9
HDR10
HDR11
I²C ep ansion
subsystem
HDR14
HDR15
RB0
RB1
SYSTEM_V
GND
R10
4.7kΩ
R11
4.7kΩ
SPI Ep ansion
subsystem
HDR12
HDR13
RC5
RC4
RC3
SYSTEM_V
GND

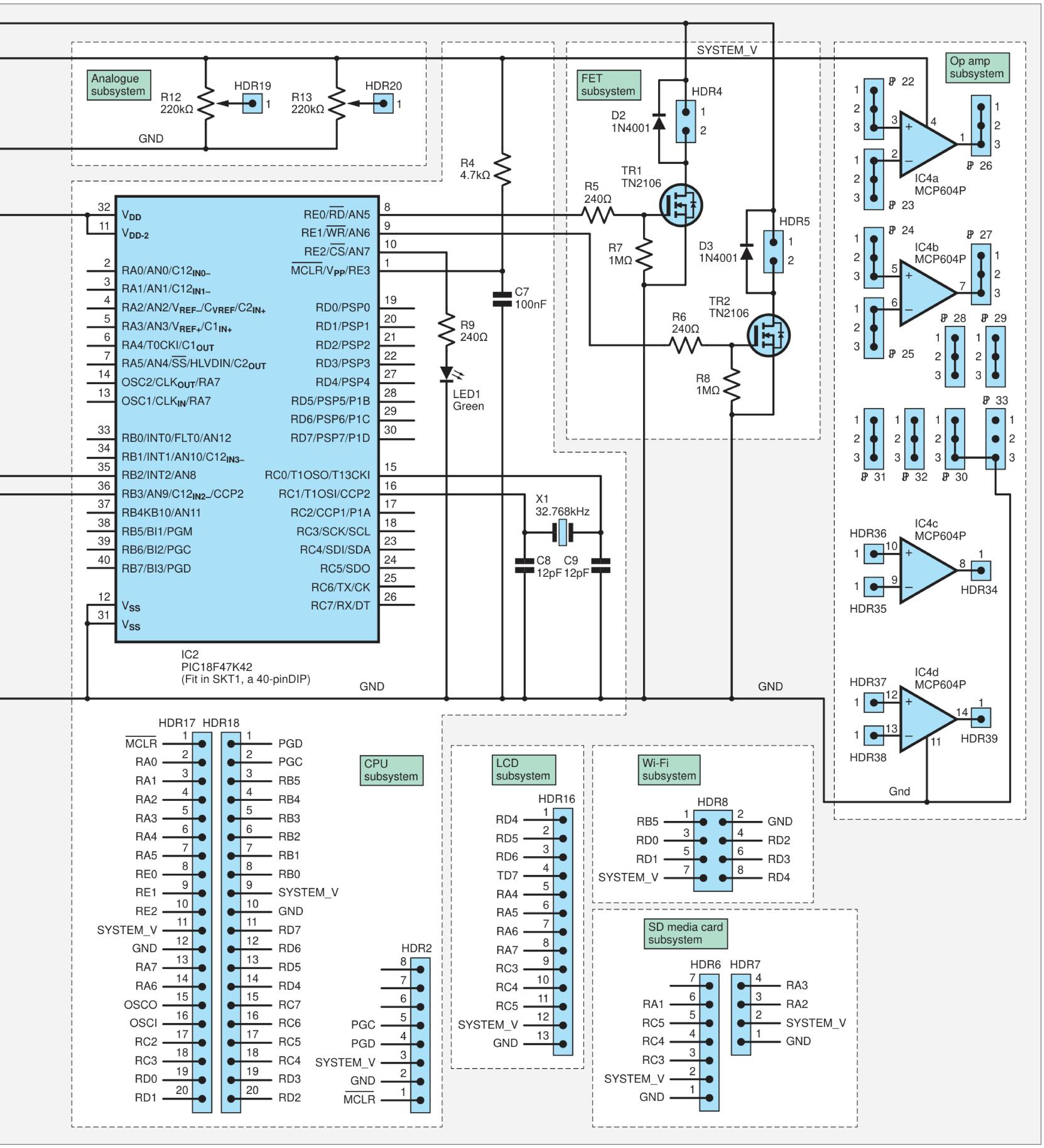
Fig.8. Our *PIC Development Board's* final schematic.

Component type count

Reducing the number of different components used is an important step in the design of any electronic product; for example, having 50 components with 50 unique values on a PCB will result in a higher cost than if there were only 20 unique values – simply because buying more of one item will give a bigger volume pricing reduction. This is why you may see some unusual values chosen for certain components in product designs – a 5.6kΩ resistor used as a pull-up instead of the more typical 4.7kΩ, perhaps because elsewhere on the circuit a 5.6kΩ resistor was required for a very specific reason. Such is the life of a product design engineer!

CPU subsystem

The processor subsystem is next. This is surprisingly simple; a standard minimum circuit from the datasheet. A resistor-capacitor circuit on the MCLR pin to provide the normal power-on reset delay, plus a few capacitors on the two voltage rails. We have decided to add the (optional) low-frequency 32kHz crystal, as that enables us to experiment with very-low-current consumption application options. (The main internal


Analogue subsystem
R12 220kΩ
HDR19
R13 220kΩ
HDR20
GND
SYSTEM_V
FET subsystem
HDR4
D2 1N4001
TR1 TN2106
R5 240Ω
R7 1MΩ
HDR5
D3 1N4001
TR2 TN2106
R6 240Ω
R8 1MΩ
GND
Op amp subsystem
IC4a MCP604P
IC4b MCP604P
IC4c MCP604P
IC4d MCP604P
HDR36
HDR35
HDR34
HDR37
HDR38
HDR39
Gnd
R4 4.7kΩ
C7 100nF
R9 240Ω
LED1 Green
X1 32.768kHz
C8 12pF
C9 12pF
VDD
VDD-2
RA0/AN0/C12IN0–
RA1/AN1/C12IN1–
RA2/AN2/VREF–/CVREF/C2IN+
RA3/AN3/VREF+/C1IN+
RA4/T0CKI/C1OUT
RA5/AN4/SS/HLVDIN/C2OUT
OSC2/CLKOUT/RA7
OSC1/CLKIN/RA7
RB0/INT0/FLT0/AN12
RB1/INT1/AN10/C12IN3–
RB2/INT2/AN8
RB3/AN9/C12IN2–/CCP2
RB4KB10/AN11
RB5/BI1/PGM
RB6/BI2/PGC
RB7/BI3/PGD
VSS
VSS
RE0/RD/AN5
RE1/WR/AN6
RE2/CS/AN7
MCLR/VPP/RE3
RD0/PSP0
RD1/PSP1
RD2/PSP2
RD3/PSP3
RD4/PSP4
RD5/PSP5/P1B
RD6/PSP6/P1C
RD7/PSP7/P1D
RC0/T1OSO/T13CKI
RC1/T1OSI/CCP2
RC2/CCP1/P1A
RC3/SCK/SCL
RC4/SDI/SDA
RC5/SDO
RC6/TX/CK
RC7/RX/DT
IC2
PIC18F47K42
(Fit in SKT1, a 40-pinDIP)
GND
HDR17 HDR18
MCLR RA0 RA1 RA2 RA3 RA4 RA5 RE0 RE1 RE2 SYSTEM_V GND RA7 RA6 OSCO OSCI RC2 RC3 RD0 RD1
PGD PGC RB5 RB4 RB3 RB2 RB1 RB0 SYSTEM_V GND RD7 RD6 RD5 RD4 RC7 RC6 RC5 RC4 RD3 RD2
CPU subsystem
HDR2
PGC PGD SYSTEM_V GND MCLR
LCD subsystem
HDR16
RD4 RD5 RD6 TD7 RA4 RA5 RA6 RA7 RC3 RC4 RC5 SYSTEM_V GND
Wi-Fi subsystem
HDR8
RB5 RD0 RD1 SYSTEM_V
GND RD2 RD3 RD4
SD media card subsystem
HDR6 HDR7
RA1 RC5 RC4 RC3 SYSTEM_V GND
RA3 RA2 SYSTEM_V GND

oscillator can be turned off completely, while the processor wakes periodically timed by the very-low-power 32kHz crystal.) That requires just a crystal and two capacitors. We added a 10µF bypass capacitor on the supply rail out of habit, this may prove to be unnecessary but it's good to have the option of one on the board. Finally, there's an LED to one of the GPIO pins, as everyone loves a flashing LED. You can see the original application circuit recommended by Microchip in Fig.5, and compare it with the final schematic in Fig.8.

Analogue subsystem

Extending the high-level design from last month, we decide to add an analogue subsystem. This will be two 'trimmer' style variable resistors, connected to the supply rails. This gives us two variable voltages, which can be connected to ADC inputs on the processor. Not only will this allow testing of ADC-software designs, but also it can provide a useful 'user interface' for some projects, such as setting an audio frequency or a delay time.

Op amp subsystem

This leaves us with the op amp circuit. Since it's an analogue circuit on a digital board it caused the greatest amount of thought. We want it to be general purpose, but the range of circuit configurations for inverting and non-inverting

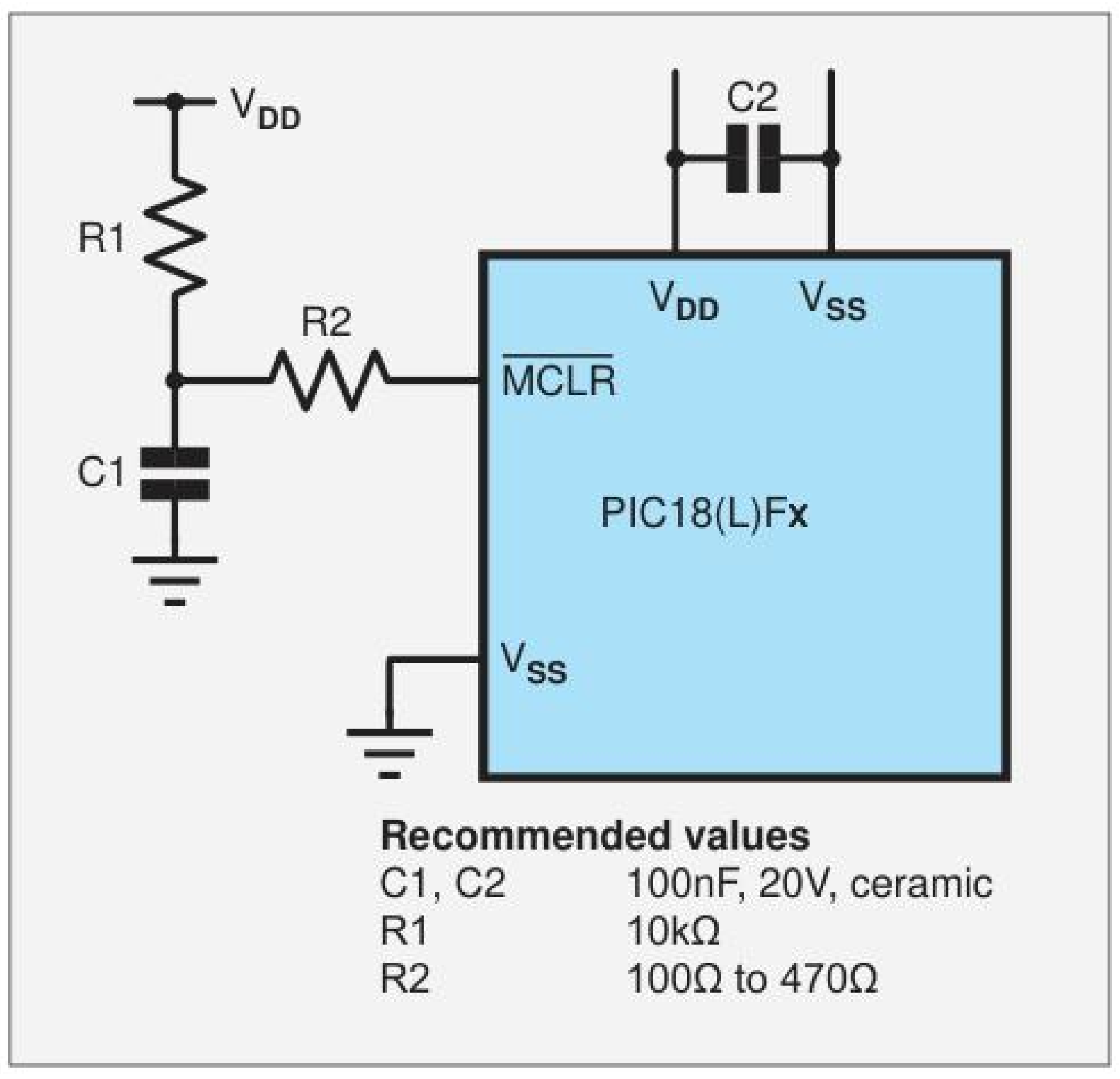


Fig.5. CPU subsystem (from Microchip datasheet 2607031).

amplifiers is huge – even before you start to bring filters into the equation. In the end, we took the lazy (and most flexible) approach – we provide power to the op amp and added pads on the input and output pins to enable you to build up any configuration you (or we) choose in future articles.

We gave this some more thought and came up with the idea of an ingenious (we hope) arrangement of solder pads that will make constructing various op amp circuits easy. A small prototyping area around the op amp, with three pads connected together, will allow for mounting resistors and capacitors around the op amps while minimising the number of wires.

We settled on the MCP604 quad op amp IC, again from Microchip, to minimise the component count. Time will tell whether this prototyping layout idea works!

The Servo motors, SD-Media, Wi-Fi and SPI/I^2C interfaces are just 0.1-inch headers with no additional components required. When it comes to connectors, the multitude of headers on our board are simple to implement as these are standard parts available within the EagleCAD libraries. The DC barrel jack on the other hand presents something of a challenge if you have not used one before. The connections to the PCB are flat tabs rather than simple round pins, which cannot be created by drilling a hole. The flat tab connections will require a small slot to be milled out of the PCB. Buried deep within the library part of the barrel jack, as can be seen in the PCB layout in Fig.6, is a routing profile. This calls for a very small routing drill, as the hole measures just 1mm wide. Thankfully, this is a normal process requirement for PCB suppliers, and the resulting PCB can be seen in Fig.7, with a perfectly created plated-through slot. You must mention the presence of this slot to your PCB supplier though, in case they miss it.

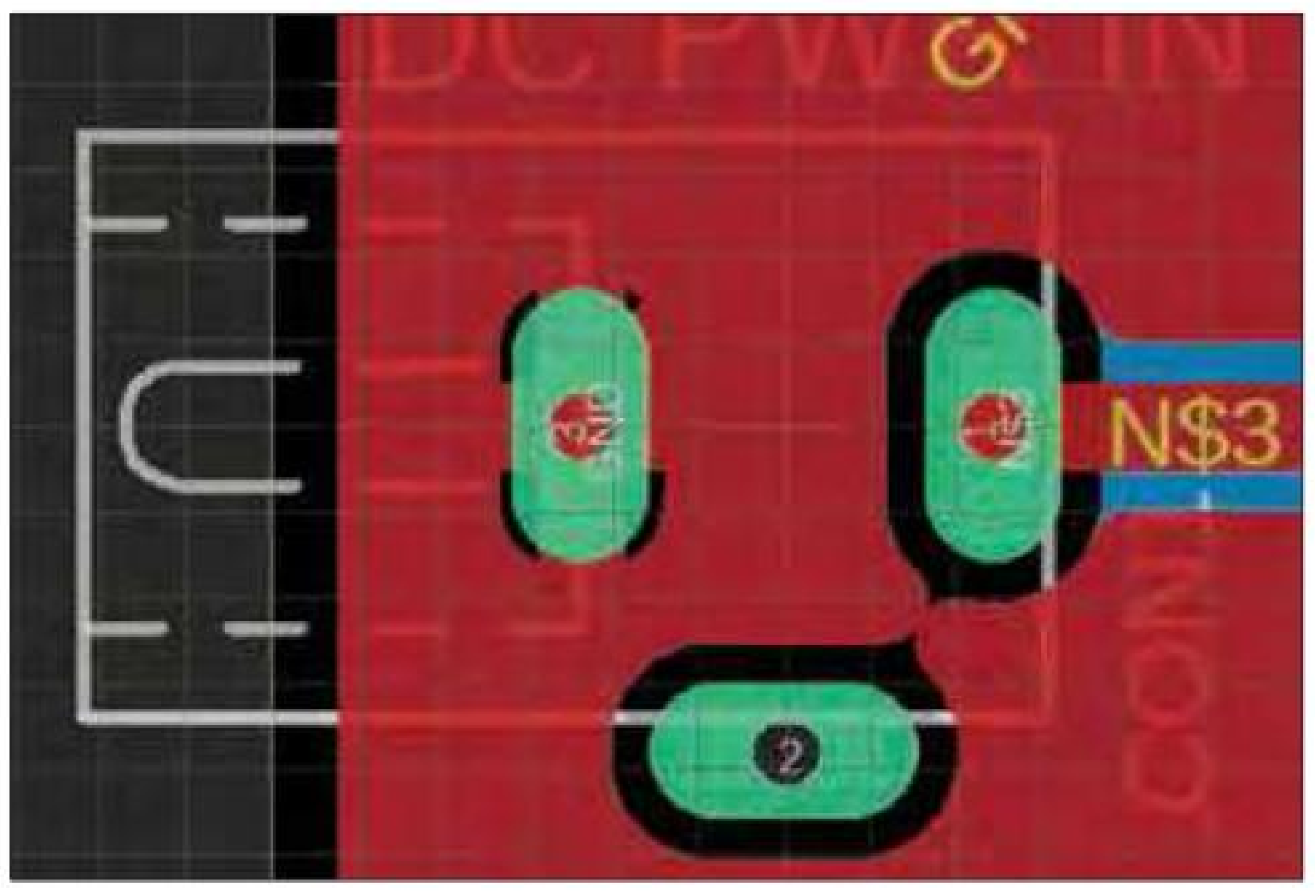


Fig.6. DC Barrel Jack PCB footprint, from EagleCAD library.

We have no need to add bypass capacitors on the DC power input, as the voltage regulator circuit has that covered. You do not want to add too much capacitance on the power rails as at some point the input capacitance will cause large inrush currents when the supply is turned on, which can introduce its own unique set of problems, typically voltage spikes on the power lines.

Finally, the schematic

Now that we know the required components we are almost ready to start drawing the schematic. We still need to check whether the components we want are available within the EagleCAD standard libraries. We start by looking for the common components, which will certainly be already present within the library, which are:

- 1/4W resistors in an axial 10mm pitch layout
- 1/4W resistors in a radial layout (might save some board space)
- Capacitors on a radial 0.1-inch pitch (low-value parts)
- Capacitors on a radial 0.2-inch pitch (high-value tantalum or electrolytic devices)
- Diodes, similar package to the resistors
- Header pins, on a 0.1-inch pitch, various lengths
- Standard, single-colour 5mm LED.

So now for the more exotic parts:

- DC Barrel Jack
- Processor
- Crystal
- MCP2221A
- LM317
- FET, TN2106
- Op amp MCP604

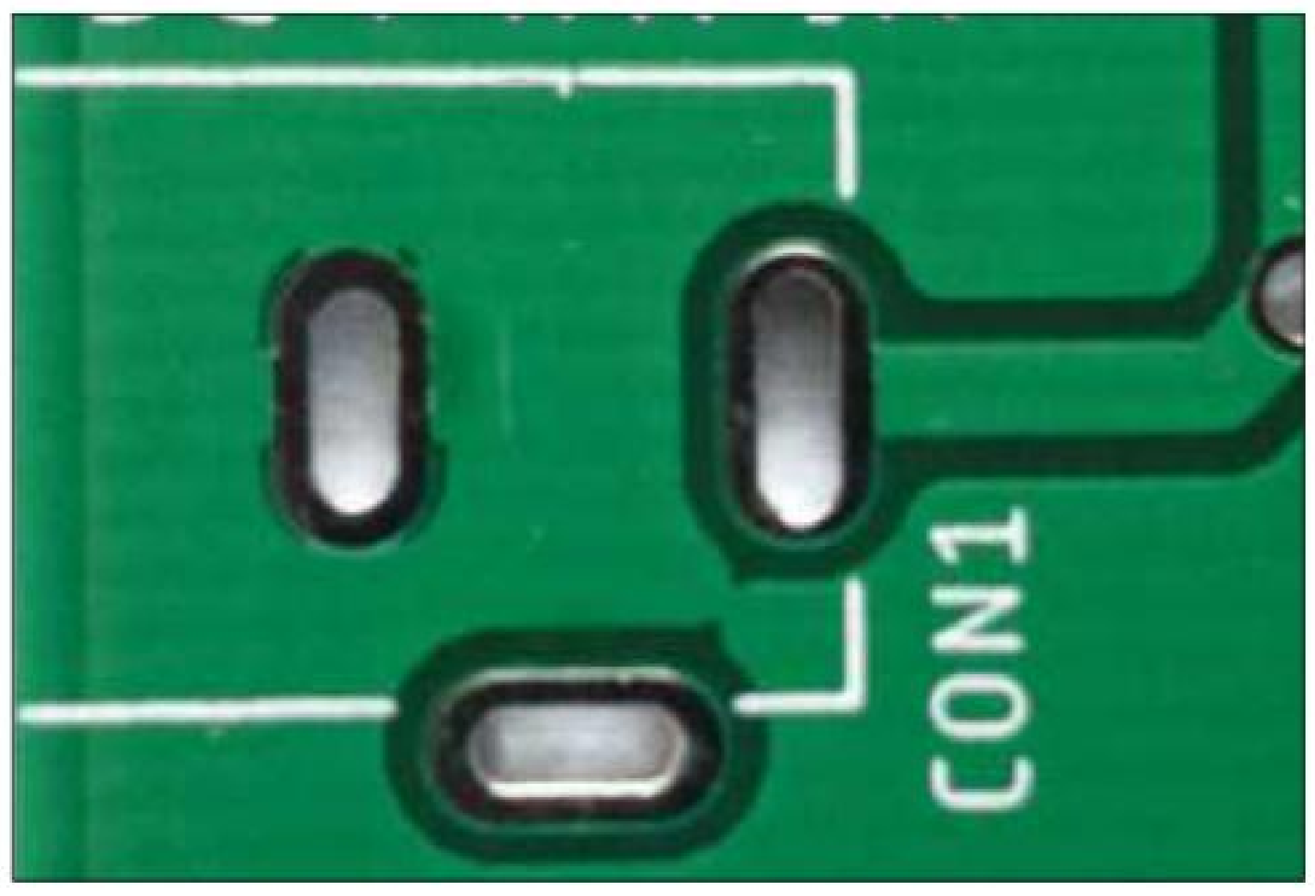


Fig.7. DC Barrel Jack footprint on a real PCB – note the slots for the jack's pads.

To our delight the MCP604 and LM317 were already present in the library.

The crystal was slightly harder to find (we like the cylindrical wire-ended 'watch crystal' format). Two parts were found in the library, but the package name did not match any part we could find on Farnell, our favourite component supplier. In the end, we temporarily placed one of the standard library crystals on our board, and carefully measured the dimensions of the holes and the silkscreen outline of the package, then compared these to the datasheet of parts on Farnell. We found a match and made a note of the Farnell part number and the library designator for the part.

Despite an extensive collection of Microchip processors in the EagleCAD library, with over 17,000 processor variants and more being released each year, it was no surprise to find our particular device – the 40-pin DIL PIC18F47K42 – was not present. However, what we did find was a PIC18F43K20 in an identical package with an identical schematic symbol. We will simply rename the part when we drop it into the schematic.

Again, it was no surprise to find that our choice of FET, the TN2106 in a TO92 package was not present. As an N-channel FET has a simple 3-pin construction, we chose the first N-channel FET already present in the library – a 2N3819. A quick look at the datasheet for this FET indicated that it would not be a suitable alternative to use directly, but the pinout is identical to the TN2106, so again we will just rename the part name when adding it to the schematic.

That leaves the MCP2221A IC. A quick search on the Internet revealed a library created, and publicly available, on **DIY-modules.org** – thank you! The library file was downloaded and copied to our EagleCAD library directory. As with all third-party library files, we did a careful check of the component's design, double checking pin connections and the dimension and positions of holes. It's an important step, but thankfully reviewing someone else's component design is a lot easier than creating your own!

So, through a combination of luck and searching the Internet we have found all of our required parts. Armed with these and the circuit subsystems, we can start to draw the schematic, pulling in the components we have identified. We start with the power supply section, then the CPU subsystem, USB IC, op amp, FETs and finally the headers. The completed schematic is shown in Fig.8. Note how the schematic does not resemble a PCB layout of the components; instead, we keep the design in a logical block layout, as this simplifies reviewing the parts and the interconnections.

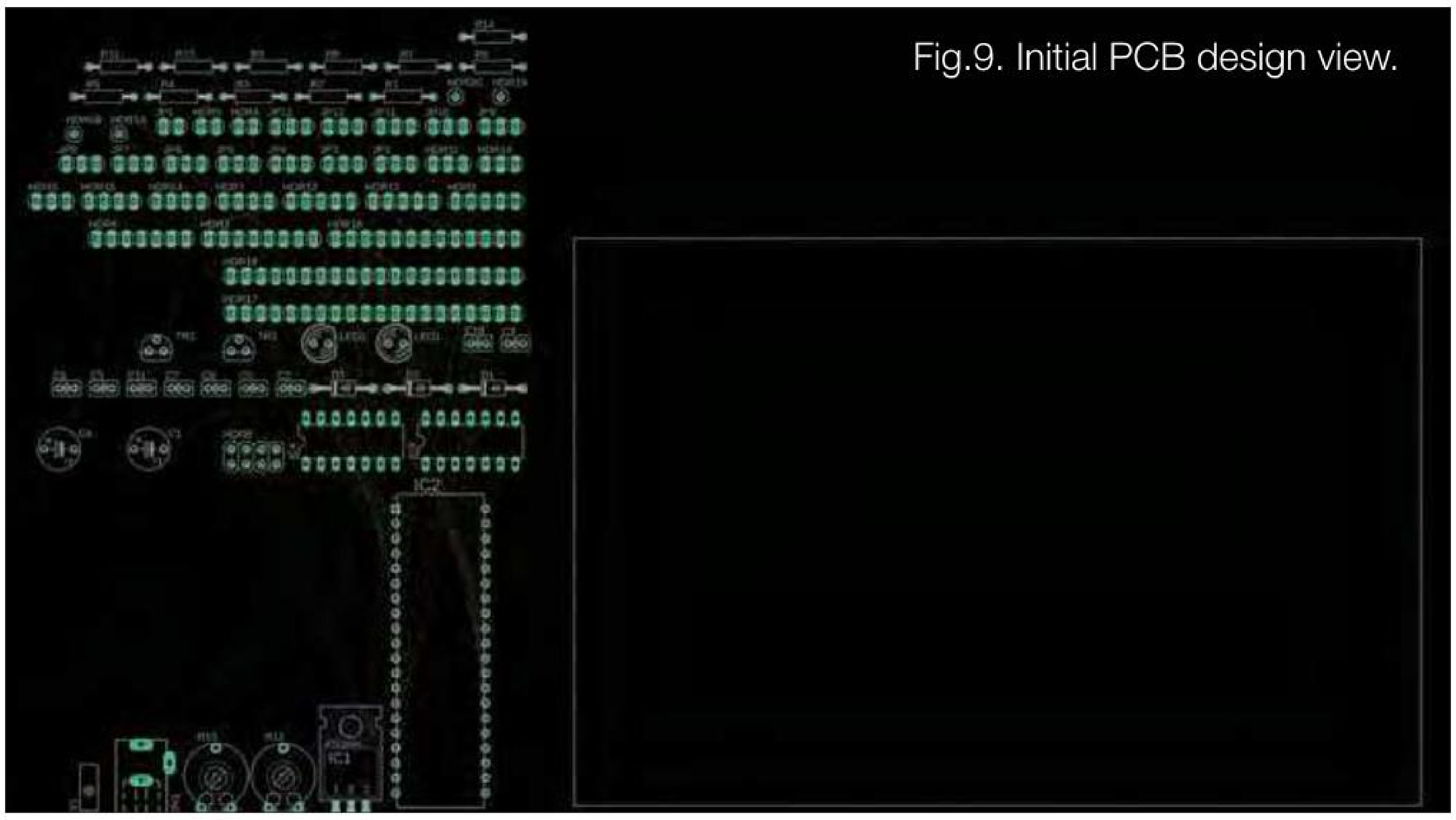


Fig.9. Initial PCB design view.

At the end of schematic design we switch to the PCB layout stage. EagleCAD creates an internal datafile called a 'netlist', which is a formal description of the parts used and the wiring connections between them. When the PCB editor opens for the first time, it shows the collection of parts on the left, with an outline for a default PCB, as shown on the right of Fig.9, which measures 160mm × 100mm. It's clear that these parts will fit a PCB of this size, but the number of interconnections that we are required to manually route for signal connections looks daunting!

The task becomes easier as you place components in their approximate intended positions. After a few hours we arrived at the component placement shown in Fig.10. Not too compact, yet we were able to reduce the board dimensions down to 150mm × 100mm. Notice how we improved the legibility of the PCB by adding helpful text and boxes to show some of the subsystems. These additions to the silkscreen content add no cost; it's just a question of how much time you want to invest in adding and tweaking details.

The routing of the signals themselves was a process of first connecting up all the power rails, using nice thick tracks, taking short routes between components. We spent an hour hand-routing the data signals, and then allowed the autorouter to finish of the final track routes. The end result, with the top layer shown in red and the bottom layer shown in blue can be seen in Fig.11.

Note that we have placed holes in the corners of the board to allow for mounting the PCB. Plus, there is plenty of space on the underside for adhesive rubber feet to allow the board, once assembled, to rest nicely on a desk. Adhesive rubber feet can be found in DIY hardware stores.

PCB sourcing

When sourcing the PCB from a supplier, we had some PCB parameters to choose from. The key points were:

PCB type	2 layer
Silkscreen Colour	Green
PCB thickness	1.6mm
PCB finish	Hot air surface levelling

These correspond with the industry 'default' values and will therefore be the cheapest option available. There are many other options to choose from, but for PCBWay and JLCPCB, these other options can be left at their default.

Five days after placing the order, the package of boards shown in Fig.12 arrived – at the same time as the components.

Assembly and testing

Now for the fun part – assembling the board. We assemble one subsystem at a time, testing each new subsystem as we proceed to simplify debugging. The boards will have had a simple electrical test after manufacture, so there should be no shorted traces or open circuits – any issues with the board after assembly will be caused by us!

It's worth noting at this point that it is rare for a PCB design to be successful on the first iteration. In our professional

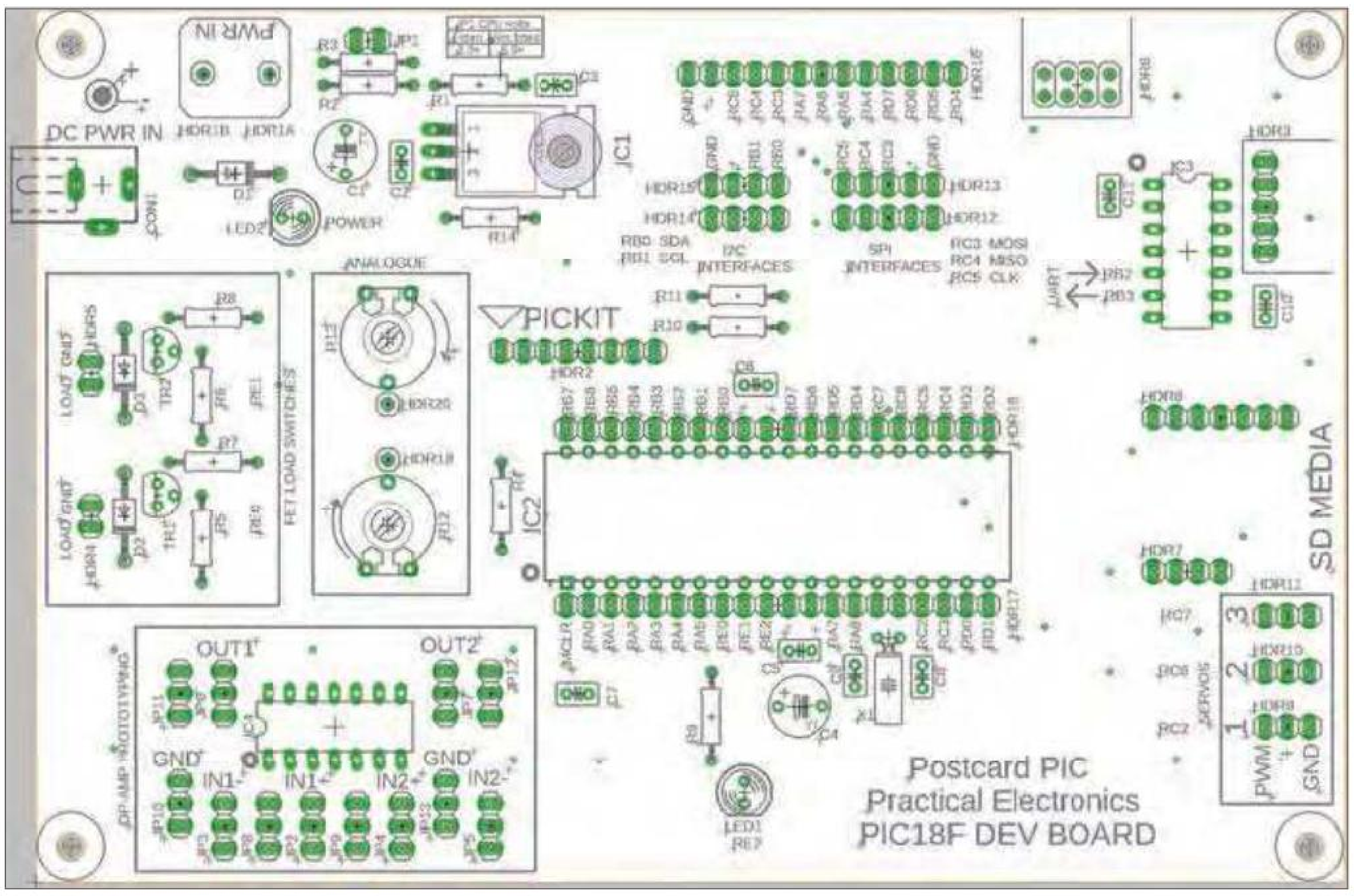


Fig.10. PCB component placement.

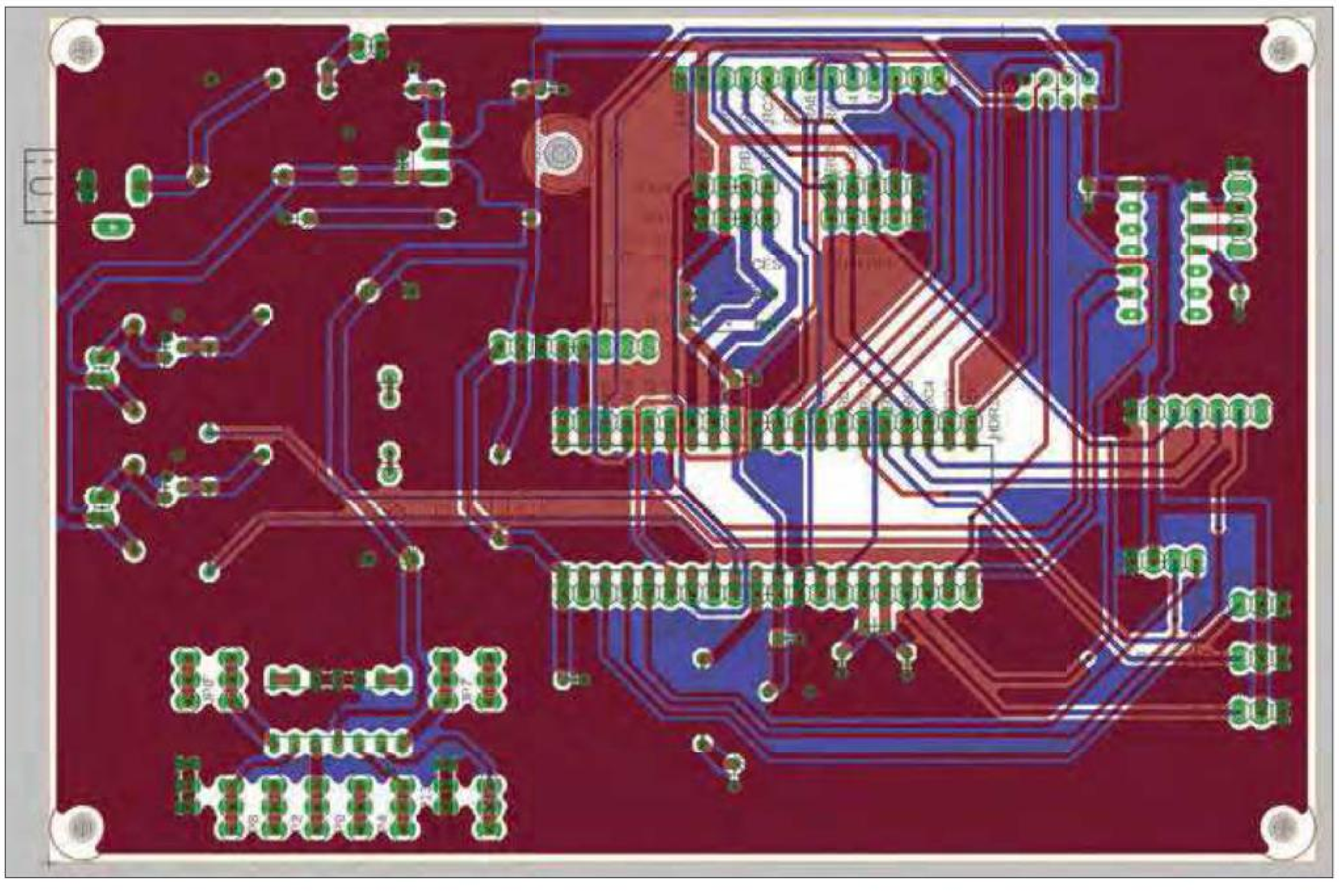


Fig.11. PCB track layout completed.

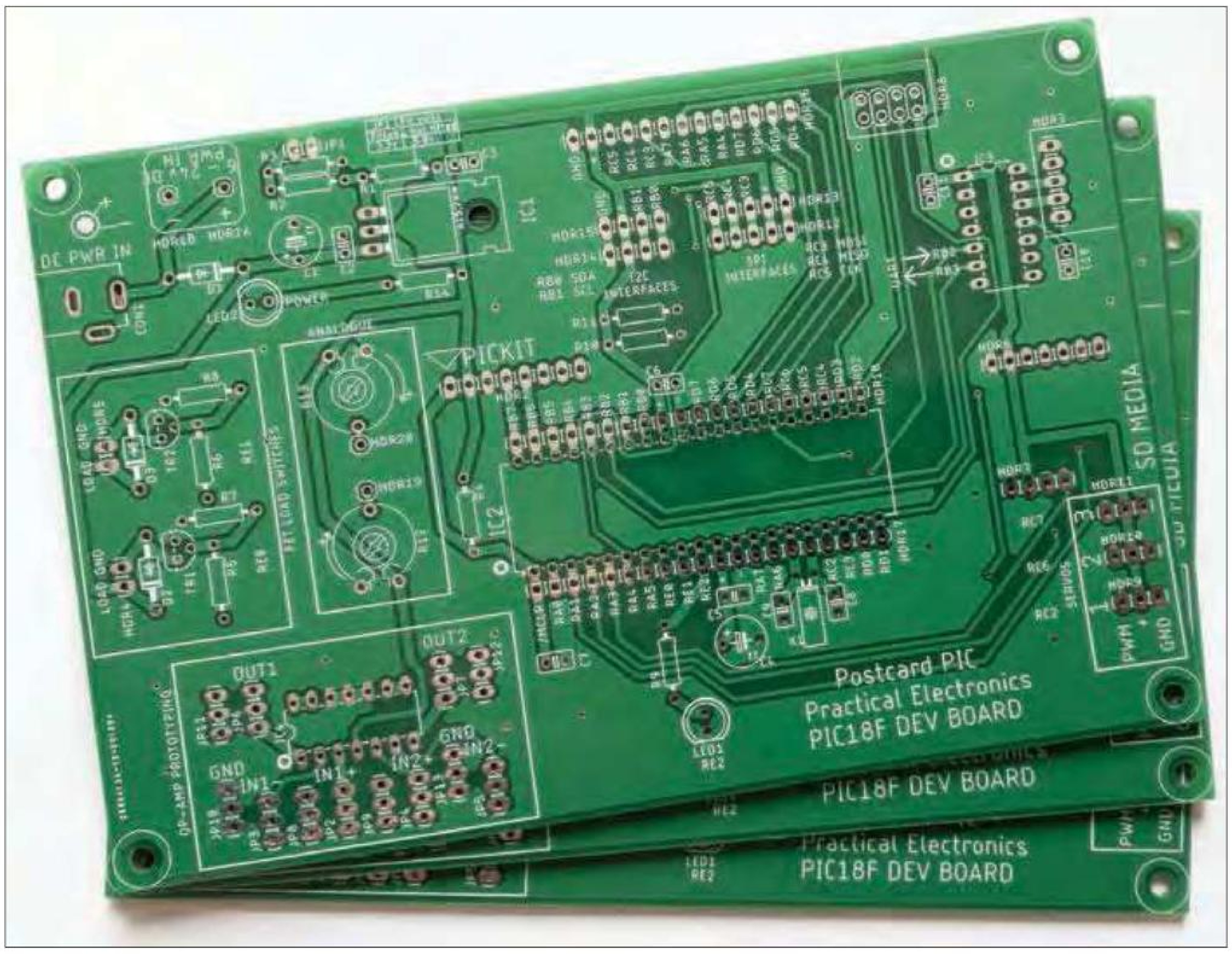


Fig.12. Real PCBs!

experience over 35 years, this has never happened. 'Unsuccessful' has quite a broad range of definitions of course, ranging from 'it catches fire when we apply power' to 'the font used on the silk screen text is incorrect'. What might be a failure for the likes of Apple may well be perfectly acceptable to us. Now is the time to find out!

Visual inspection

The first thing we do, before soldering a single component, is visually inspect the PCB. There is a fairly standard checklist:

- Are the PCB dimensions acceptable? When designing a board, we sometimes need it to fit in an enclosure with precision. We check that the PCB has the correct outline and any slots cut as specified. This is not an issue for us, as we are not fitting the board into an enclosure, but it's worth checking that the dimensions are correct, within tolerance, as it confirms the quality assurance of the manufacturing process. Errors in something as simple as the board outline could signal more concerning issues later on.
- Are all the silkscreen details present? This is something that you can get caught out on when designing a board. You may put text or graphics on a particular layer, but then forget to include that layer in the Gerber pack you send to the manufacturer (happened to us more than once!)
- Are all the silkscreen details legible? It's too easy to specify thin text or graphic details that look great on screen, but look terrible with the manufacturer's process. It's not an exact science and difficult to judge when you are looking at a perfectly rendered design in a CAD package.
- Are all the holes and milling profiles aligned? It's possible that the centre of the drill holes may not line up with the PCB pads, either because of poor manufacturing tolerance, or a misinterpretation of the CAD data (PCB tracks and drill positions are held in different files, in different data formats.)
- Are all the holes and milling profiles suitable for use? Sometimes, component legs may be thicker than expected, and will not fit in the holes. Connectors with wide flat pins – like our DC power jack – require milling rather than drilling. Did the manufacturer spot this, and are the dimensions OK for your actual connector?

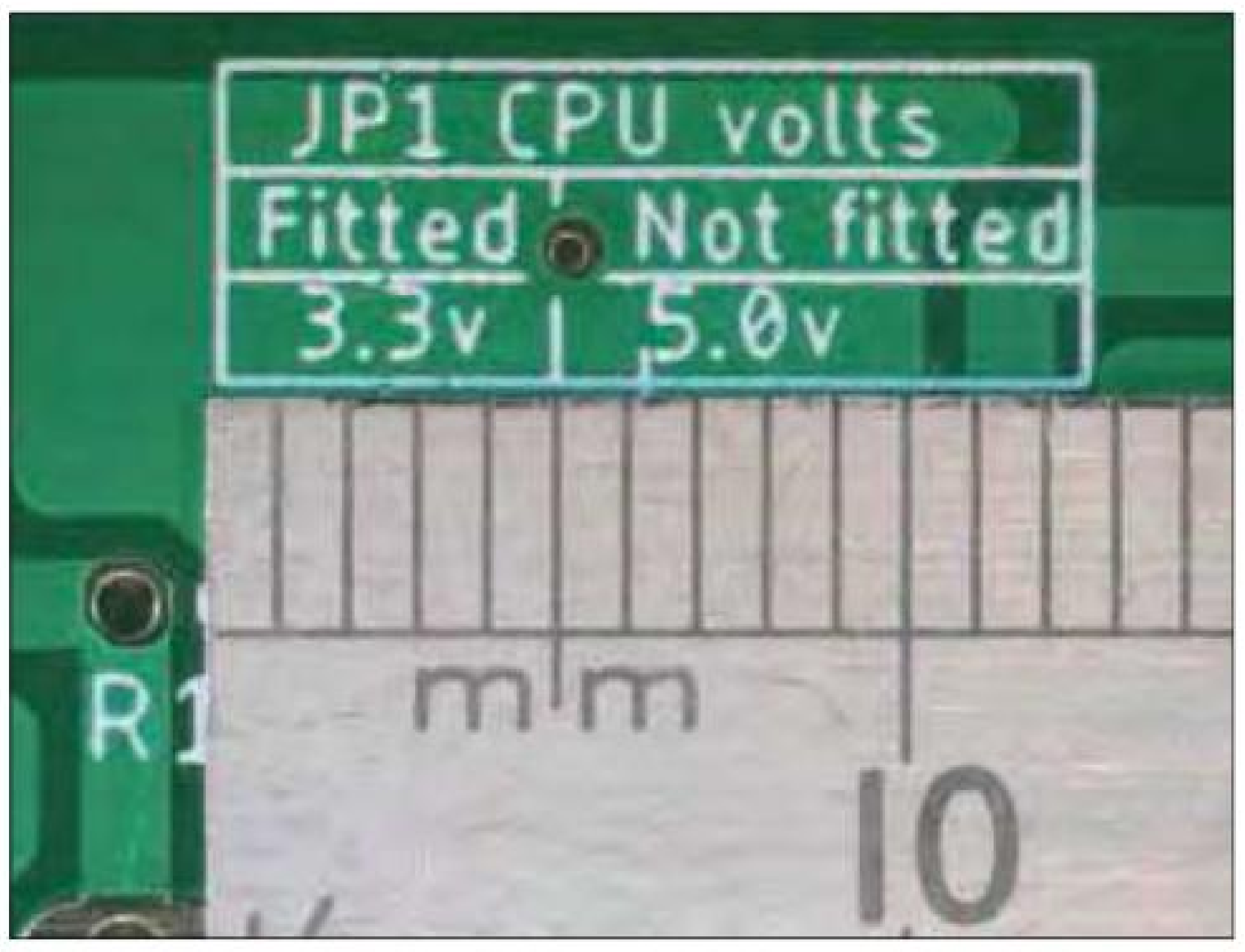


Fig.13. Silkscreen print detail.

Once these checks are complete, you can relax a little.

When we examined our board, we spotted one small issue – the header pin interface HDR8, on the top right of the board, does not include the text 'Wi-Fi', to indicate the module intended to connect to it. This is a very small point – people using this board will know the purpose of the connector, and the Wi-Fi module can fit on only one header – but it's an annoying omission. The silk screen layer on the PCB is our 'canvas', and at no additional cost we can print whatever we want on it, so to miss printing something that is useful is regrettable. We will correct that in the final PCB design. Our smallest silkscreen print detail, shown in Fig.13, came out very clearly with all text visible, so that's a plus point.

Now we can look more closely at the manufacturing detail, with the aid of a magnifying glass.

Are the drills nicely centred in the pad holes? By this we mean, is there a good amount of copper around any through-plated holes?

How well is the solder-resist aligned with the pads? In our design, where all components are soldered manually, this is not an important point; but with surface-mount components, a poorly aligned solder resist print could mask parts of pads which should be clear. As you can see in Fig.14, there is an offset in the solder resists outline, but it is within the manufacturer's stated tolerances and causes us no issues.

Then a second issue was found – the holes for the MicroSD card holder have the card entry slot pointing inwards, not away from the PCB. While this will work OK, it is not what we had intended. That was a simple design error on our part, and rather surprising too, as it was a point we thought about during the design. Not sure how that slipped through, but that is why we prototype, check – and check again.

Initial assembly and testing

We build the power supply section first, perform a quick continuity check across the supply pins, then apply 9V DC input. We measured 5.3V without the header fitted, and 3.4V with it fitted. Current consumption (without any load at this stage) is 5.7mA, which is almost exactly the current through R1, R2 and R3 – as expected. We can now fit the power LED.

Next, the CPU subsystem – just the minimal parts: the IC socket, the PIC debug header and the CPU. Using MPLAB IPE

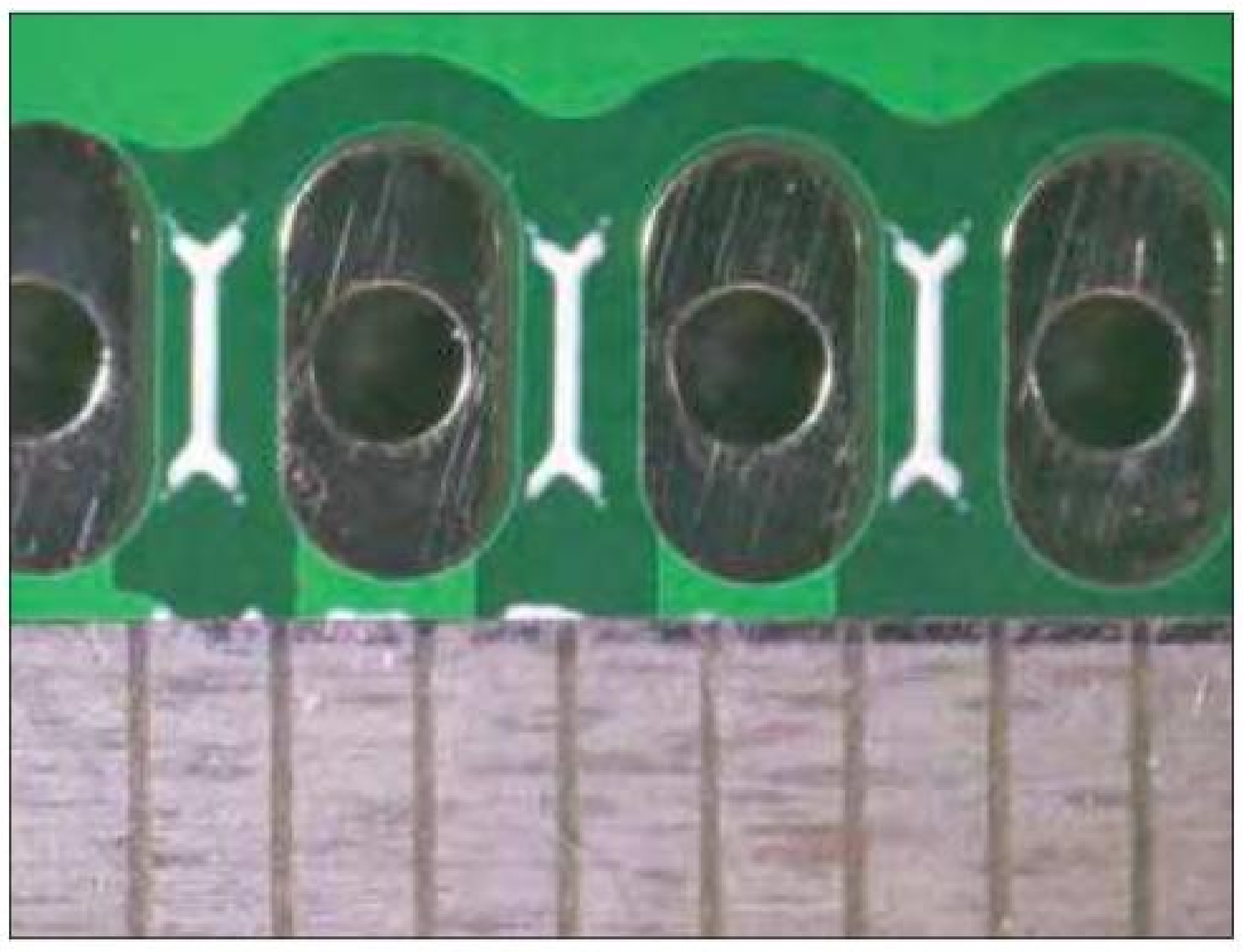


Fig.14. Solder resist layer (mis)alignment.

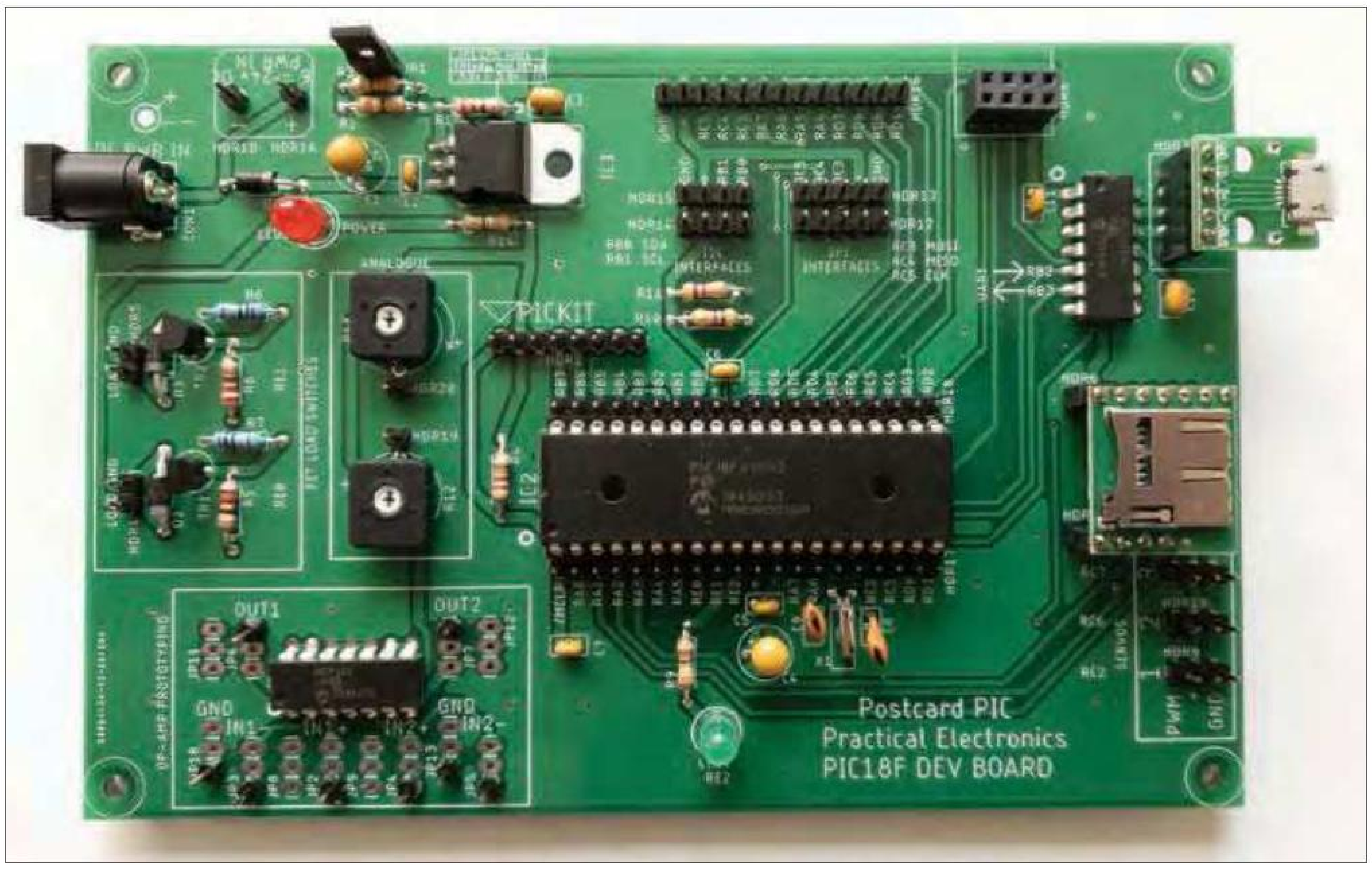


Fig.15. At last! – we have a built *PIC Development Board*. It's not yet fully tested, but so far it looks very promising.

we connect to the MCU. After confirming the device can be read, we proceeded with fitting the remaining CPU subsystem components (MCLR pull-up, capacitors and the user LED) then checked the PIC could be read again. Current consumption rose to 16mA, due to the processor running 'blank' code.

FETs next, followed by the USB IC and the op amp. A recheck of the current consumption shows no significant increase, so we finish off by installing all the 0.1-inch-pitch header pins, and the four header sockets for the Wi-Fi, USB and SD-Media interface boards.

Now we can test a peripheral. We start with the easiest, a servo motor. The interface works, and with two plugged in we check current consumption. An extra 20mA at 5V, and no significant heat increase from the regulator, even without a heatsink fitted.

The USB interface was a joy to test – we do not have a USB software stack to mess with, as the MCP2221A IC provides us with a UART interface to the processor. We simply enabled the UART interface in software, mapped the UART RX and TX signals to the correct pins (as shown on the silkscreen) and success. So easy, and cheaper than buying an FTDI USB-to-UART cable.

The Wi-Fi interface was validated by routing the Wi-Fi's UART interface through the processor and out to the USB serial interface, making the processor appear as a 'pass-through' wire. With a terminal program running on a PC, we were able to send AT commands to the ESP-01 module. Another subsystem ticked off.

Testing the other subsystems – the Micro SD-Media interface, the analogue and op amp circuits – will have to wait until next time, but so far things are looking great for the first revision of the PIC18F development PCB.

Summary

In our next article we will cover the software side of testing, as this will introduce the MPLAB-X IDE, and the MCC Code Configurator tool, which simplifies the setup of the drivers for the various peripherals on the microcontroller.

We will also present the parts list and PCB ordering details once validation has completed, so you can follow along with your own *PIC Development Board* hardware.

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Max's Cool Beans

By Max the Magnificent

Flashing LEDs and drooling engineers – Part 13

Eeek! I can't believe that we are already at Part 13 of this magnificent mini-mega-series. Hmmm, 'thirteen'. I have a friend who refuses to leave his house on a Friday, 13th, although this number is 'Lucky for some,' as they say.

Are you confused?

When we have pixels (in the form of tricolor LEDs, in our case) arranged in rings, one of the things we commonly want to do is to cycle around, turning a new pixel on and an old pixel off at the same time. We've talked about various techniques we can use to achieve this in previous columns. Sad to relate, however, several readers have emailed me to say that they remain baffled, confounded, confused, and perplexed – possibly because we couldn't restrain ourselves from introducing and investigating a cornucopia of alternative approaches as we meandered along. So let's take a moment to gather all of these tactics together in one place and do our best to demystify things.

In the case of my *Prognostication Engine* project, the rings each have 16 pixels. However, as I noted in a previous column (*PE*, January 2021), when I'm trying to wrap my brain around something, I first like to simplify the problem, which – in this case – means reducing the number of pixels. Given a choice, we want to come up with a generic solution that can work for any number of pixels, so I typically opt for a small prime number on the basis that, if our solution works for this, it will work for anything.

Thus, purely for the purposes of our thought experiments, let's assume we have a 5-pixel ring and that our pixels are numbered clockwise, starting with 0 at the top (Fig.1a). Sometimes we may wish to set a single pixel racing round the ring in a clockwise direction (Fig.1b); other times, we may opt for a widdershins (a.k.a. counterclockwise a.k.a. anticlockwise) rotation (Fig.1c).

To keep these discussions general, let's assume that that the number of pixels we are playing with is defined as `NUM_P`, which will be 5 in the case of this example. Also, since our pixels are numbered from 0 to 4, let's also assume we've defined `MAX_P` as being `(NUM_P - 1)`, because this will save us from having to subtract 1 all the time.

As we've discussed in earlier columns, if we are implementing a clockwise rotation, and if we are currently poised to activate pixel `P`, then most of the time we want to deactivate pixel `(P - 1)`. It's only when we wish to activate pixel 0 that we need to deactivate pixel `MAX_P`. Similarly, if we are implementing an anticlockwise rotation, and if we are currently about to activate pixel `P`, then most of the time we want to deactivate pixel `(P + 1)`. It's only when we wish to activate pixel `MAX_P` that we need to deactivate pixel 0.

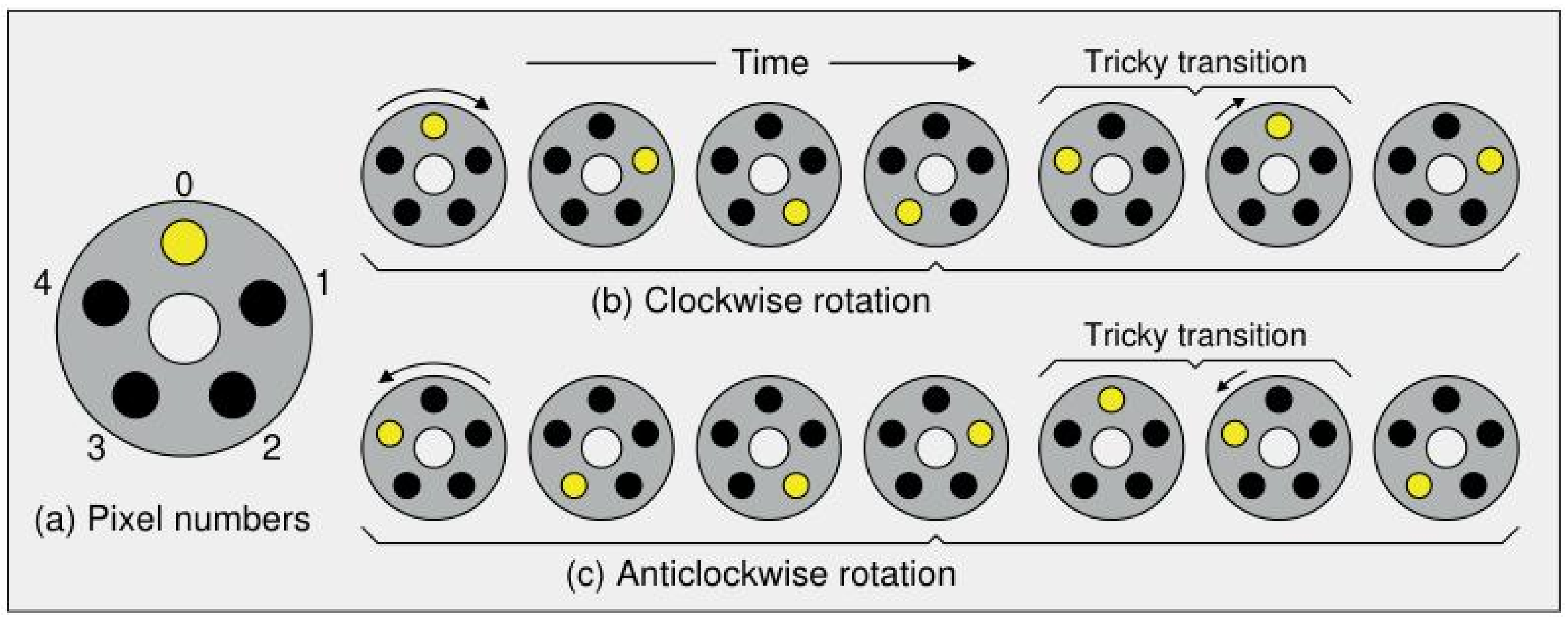


Fig.1. Clockwise and anticlockwise rotations.

Testing times

One solution is to perform a simple test to determine which pixel is to be deactivated. Assuming a clockwise rotation, our main `loop()` function could be written as follows (where the test is shown in bold).

```
void loop ()
{
   for (int iPix = 0; iPix <= MAX_P; iPix++)
   {
      // Turn new pixel on
      Neos.setPixelColor(iPix, COLOR_ON);

      // Turn old pixel off
      if (iPix = 0)
         Neos.setPixelColor(MAX_P, COLOR_OFF);
      else
         Neos.setPixelColor((iPix - 1), COLOR_OFF);

      // Display the result
      Neos.show();
      delay(PadDelay);
   }
}
```

It's probably worth noting that in previous programs we've used the equivalent of `iPix < NUM_P` (which equates to `iPix < 5` in this example) as the test condition in our `for()` loop. The reason we are using `iPix <= MAX_P` (which equates to `iPix <= 4`) as the test condition in this example is that it will better complement the experiments that are to come. The main point to note here is that they both result in the same actions, as seen by the person watching the ring perform its magic.

If you wish to peruse and ponder this in more detail, the full sketch (program) is presented in file **CB-Mar21-01.txt** (it, and any other files associated with this article, are available on the March 2021 page of the *PE* website: **https://bit.ly/3oouhbl**).

If you do look at the full sketch, you'll see that we've set the cycle time – that is, the time taken to perform a complete revolution of the ring – to be 1,000ms (milliseconds) – ie, one second. We also make the assumption that it takes 1ms to perform any calculations and upload new values for each pixel position. Based on this, we calculate an appropriate value for the `PadDelay` variable in our `setup()` function.

We could use a similar testing approach to perform a counterclockwise rotation, as illustrated below (file **CB-Mar21-02.txt**). In this case, we've highlighted any changes to our previous code in bold.

```
void loop ()
{
  for (int iPix = MAX_P; iPix >= 0; iPix--)
  {
     // Turn new pixel on
     Neos.setPixelColor(iPix, COLOR_ON);
```

```
      // Turn old pixel off
      if (iPix == MAX_P)
         Neos.setPixelColor(0, COLOR_OFF);
      else
         Neos.setPixelColor((iPix + 1), COLOR_OFF);

      // Display the result
      Neos.show();
      delay(PadDelay);
   }
}
```

Before we move on, it's worth reminding ourselves that `iPix – 1` or `iPix + 1` works just fine most of the time. The only reason we have to perform the aforementioned tests is to handle the boundary values that occur at the beginning of the loop (or the end of the loop, depending on your point of view).

Magnificent modulos

Using tests (as discussed above) certainly provides serviceable solutions. On the other hand, they feel a little 'messy' somehow. As you may recall, the modulo operator `%` returns the integer remainder from an integer division. Well, this is one of those cases where the modulo operator really gets a chance to 'strut its stuff,' as it were.

Since I'm not a natural programmer, I typically sketch things out on paper first. Let's start with a clockwise rotation (Fig.2a). Based on our earlier sketches, we know that – for each step around the ring – what we've got is the number of the new pixel to be turned on, while what we want is the number of the old pixel to be turned off. If we add `MAX_P` (which is the number of pixels minus one) to the number of the pixel we just turned on, and then perform a modulo division with `NUM_P` (the number of pixels), we end up with the value we desire. The code for this is shown below with the interesting parts highlighted in bold (file **CB-Mar21-03.txt**).

```
void loop ()
{
   int tPix;

   for (int iPix = 0; iPix <= MAX_P; iPix++)
   {
      // Turn new pixel on
      Neos.setPixelColor(iPix, COLOR_ON);

      // Turn old pixel off
      tPix = (iPix + MAX_P) % NUM_P;
      Neos.setPixelColor(tPix, COLOR_OFF);

      // Display the result
      Neos.show();
      delay(PadDelay);
   }
}
```

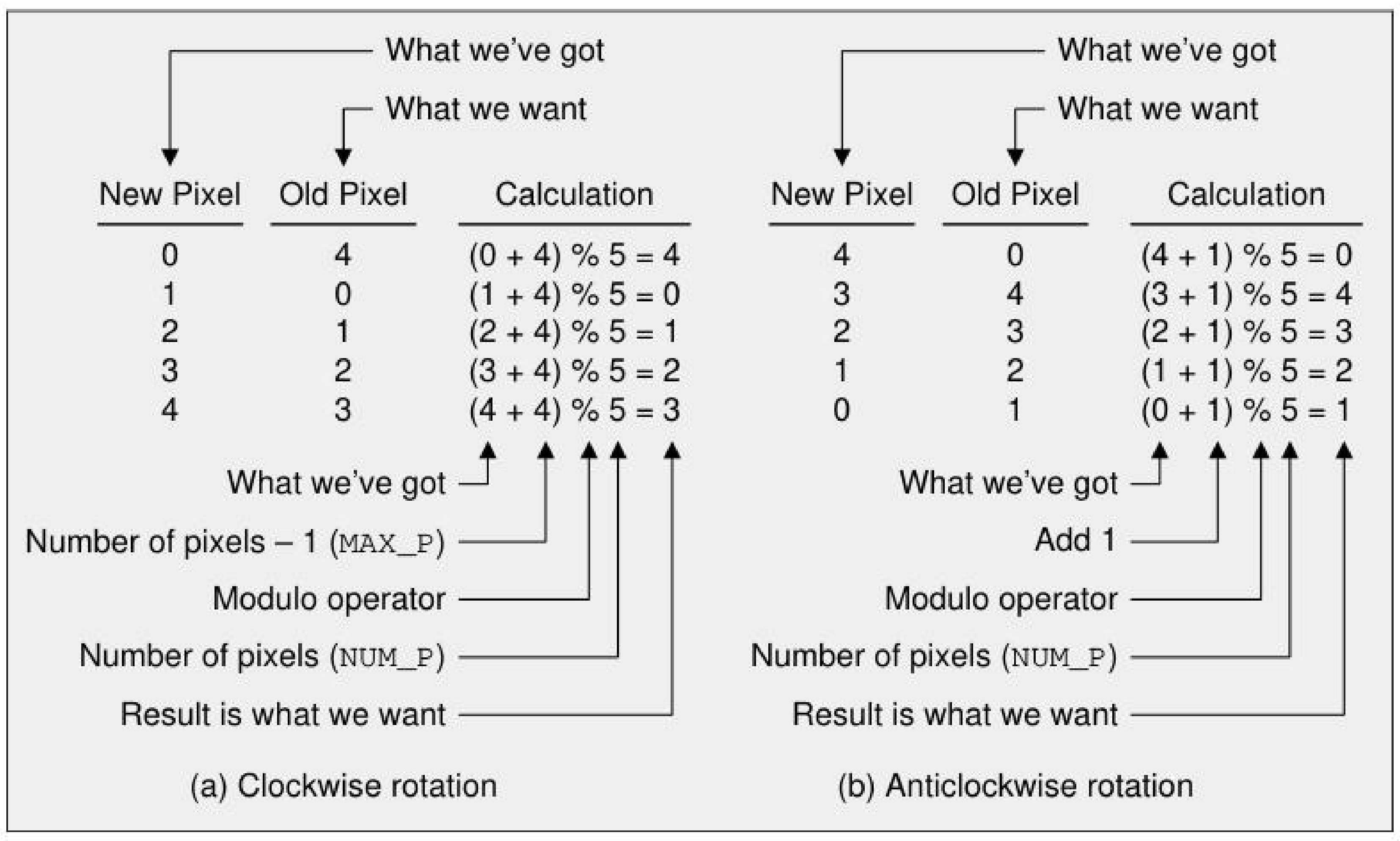


Fig.2. Using the modulo operator to give us what we want.

Similarly, if we wish to perform an anticlockwise rotation (Fig.2b), then for each step around the ring, we know the number of the new pixel to be turned on and we need to calculate the number of the old pixel to be turned off. In this case, if we add 1 to the number of the pixel we just turned on and then perform a modulo division with `NUM_P` (the number of pixels), we end up with the value we desire. The code for this is shown below with the interesting parts highlighted in bold (file **CB-Mar21-04.txt**).

```
void loop ()
{
   int tPix;

   for (int iPix = MAX_P; iPix >= 0; iPix--)
   {
      // Turn new pixel on
      Neos.setPixelColor(iPix, COLOR_ON);

      // Turn old pixel off
      tPix = (iPix + 1) % NUM_P;
      Neos.setPixelColor(tPix, COLOR_OFF);

      // Display the result
      Neos.show();
      delay(PadDelay);
   }
}
```

It's rude to point

I don't know about you, but when I was a kid and I tried to direct my mother's attention to something of interest (like an old lady with a huge wart on the end of her nose, just to pick an example out of thin air), she would inform me by means of a menacing whisper that 'It's rude to point,' after which we would suddenly discover that our presence was required elsewhere.

Of course, my mother wasn't into programming, or so I assume, but – now I come to think about it – I didn't even know she spoke fluent French and German until after I'd left home, so maybe she programs like a diva. Be that as it may, pointers can be jolly useful in the context of programs.

Now, I should point out that I'm not talking about true C pointers, which – although they are extremely efficacious – are a completely different kettle of fish and a topic in their own right. For the purposes of this column, I'm visualising a simple pseudo pointer implemented using an integer.

As usual, we'll start with a clockwise rotation. Let's assume that we declare a global integer variable called `NewP` ('new pixel'); also, that we initialise this to contain 0. In this case, the code for our main `loop()` function could be as follows (file **CB-Mar21-05.txt**).

```
void loop ()
{
   int oldP;

   // Turn new pixel on
   Neos.setPixelColor(NewP, COLOR_ON);

   // Turn old pixel off
   oldP = (NewP + MAX_P) % NUM_P;
   Neos.setPixelColor(oldP, COLOR_OFF);

   // Display the result
   Neos.show();
   delay(PadDelay);

   // Increment the pointer
   NewP = (NewP + 1) % NUM_P;
}
```

Observe that we no longer require the `for()` loop. Also, that we are using exactly the same modulo operation to calculate the number of the old pixel to be turned off (we just tweaked the name of the variable). The only other modification is that we now need to increment the value of our integer pointer at the end of the loop. As we see, we are using the modulo operator once again to ensure that `NewP` follows the sequence 0, 1, 2, 3, 4, 0, 1, 2...

Of course, if we were to perform an anticlockwise rotation, we would want `NewP` to follow the sequence 4, 3, 2, 1, 0, 4, 3, 2... Just for giggles and grins, why don't you try creating the counterclockwise version of this technique for yourself – even if only as a pencil and paper exercise – before we proceed further.

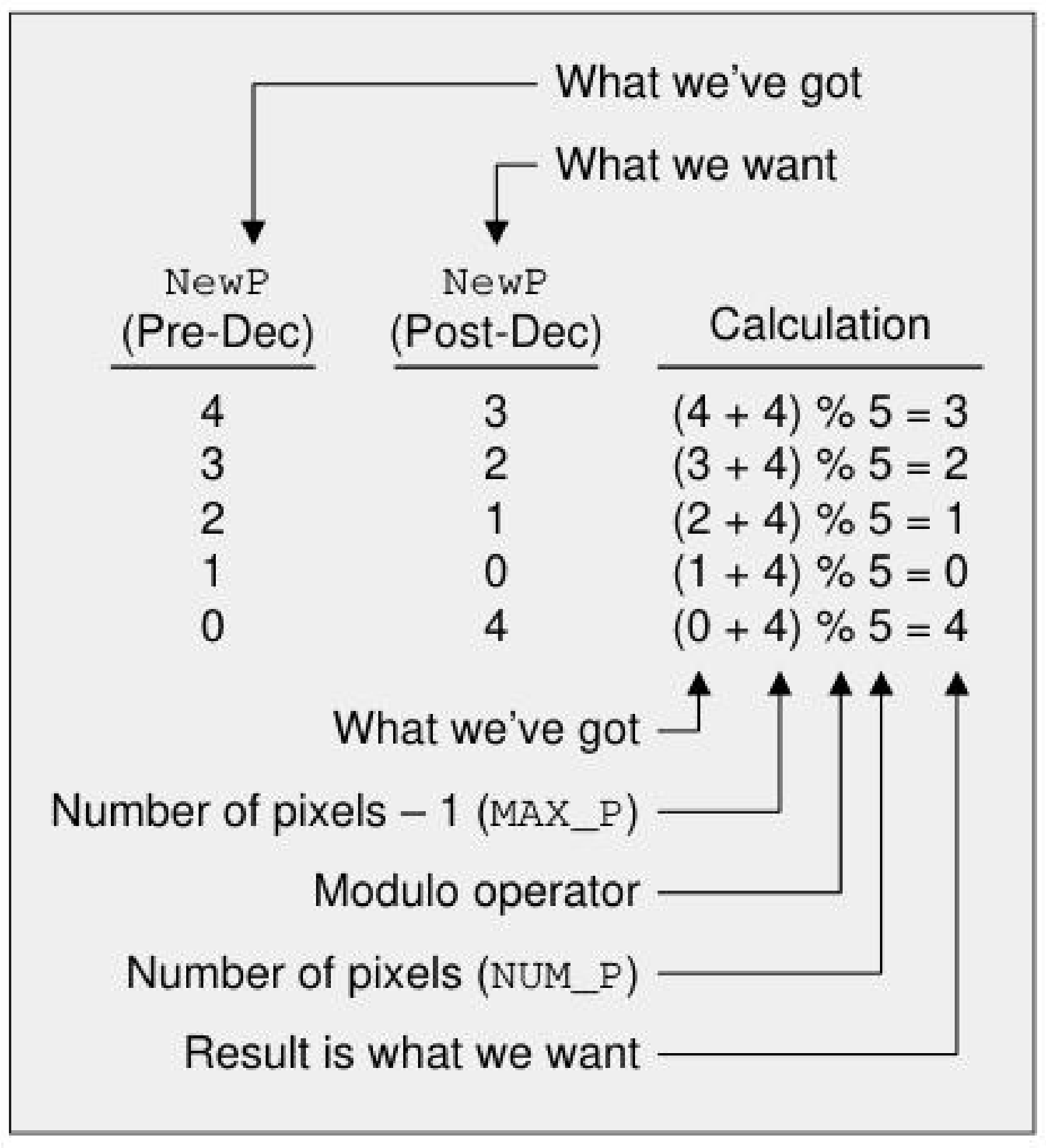
What? You've finished already? I'm proud of you! As you may have come to realise, if we are performing an anticlockwise rotation, then when it comes to decrementing the pointer at the end, we can't use anything along the lines of `NewP = (NewP - 1) % NUM_P`. This is because when you get to `NewP` being 0, then `NewP - 1` will equal –1, and we don't want to dive into the morass of complications and tribulations that will ensue if we apply the modulo operator at this point (see also this month's *Tips and Tricks*).

The solution I came up with is as follows (file **CB-Mar21-06.txt**). The part where we turn the old pixel off is based on our previous anticlockwise routine. The part that is of interest is where we decrement our pointer at the end.

```
void loop ()
{
   int oldP;

   // Turn new pixel on
   Neos.setPixelColor(NewP, COLOR_ON);

   // Turn old pixel off
   oldP = (NewP + 1) % NUM_P;
   Neos.setPixelColor(oldP, COLOR_OFF);

   // Display the result
   Neos.show();
   delay(PadDelay);

   // Decrement the pointer
   NewP = (NewP + MAX_P) % NUM_P;
}
```

The key point to note – apart from the fact it works – is the fact that we are using (`NewP + MAX_P`) means that we always have a positive number to feed to our modulo operator. It might be useful for you to jot down what you think is going on, and then take a look at Fig.3 to see how I visualise this.

Did you spot anything interesting about Fig.3? How about the fact that this calculation is identical to that shown in Fig.2a (it's just that we've reordered things a little)? Of course, this makes total sense when you think about it. Previously, we were using our equation to calculate the *old* pixel to turn *off* while performing a *clockwise* rotation. Now, we are using the same equation to calculate the *new* pixel to turn *on* while performing an *anticlockwise* rotation. Scary as it seems, it's almost as if we had a clue what we were doing.



NewP (Pre-Dec)	NewP (Post-Dec)	Calculation
4	3	(4 + 4) % 5 = 3
3	2	(3 + 4) % 5 = 2
2	1	(2 + 4) % 5 = 1
1	0	(1 + 4) % 5 = 0
0	4	(0 + 4) % 5 = 4

Fig.3. Modulo everywhere you look.

Chickens and eggs

All sorts of things keep popping into my head while I'm writing this. For example, our previous examples have involved first turning the current pixel on and then calculating the old pixel to be turned off. We could, of course, do things the other way around – that is, turn the current pixel off and then calculate the new pixel to be turned on.

Let's take our previous clockwise rotation example (file **CB-Mar21-05.txt**) and modify it to reflect this new scenario (file **CB-Mar21-07.txt**). In this case, our main `loop()` function might appear as follows:

```
void loop ()
{
   // Turn old pixel off
   Neos.setPixelColor(CurrentP, COLOR_OFF);

   // Increment the pointer
   CurrentP = (CurrentP + 1) % NUM_P;

   // Turn new pixel on
   Neos.setPixelColor(CurrentP, COLOR_ON);

   // Display the result
   Neos.show();
   delay(PadDelay);
}
```

If you compare the two solutions, you will observe that our new version is a tad more concise and correspondingly more efficient. Previously, we had to calculate the number of the old pixel and also the value of the new pointer, which therefore required two modulo operations. By comparison, our new incarnation requires only a single modulo operation. Tra-la!

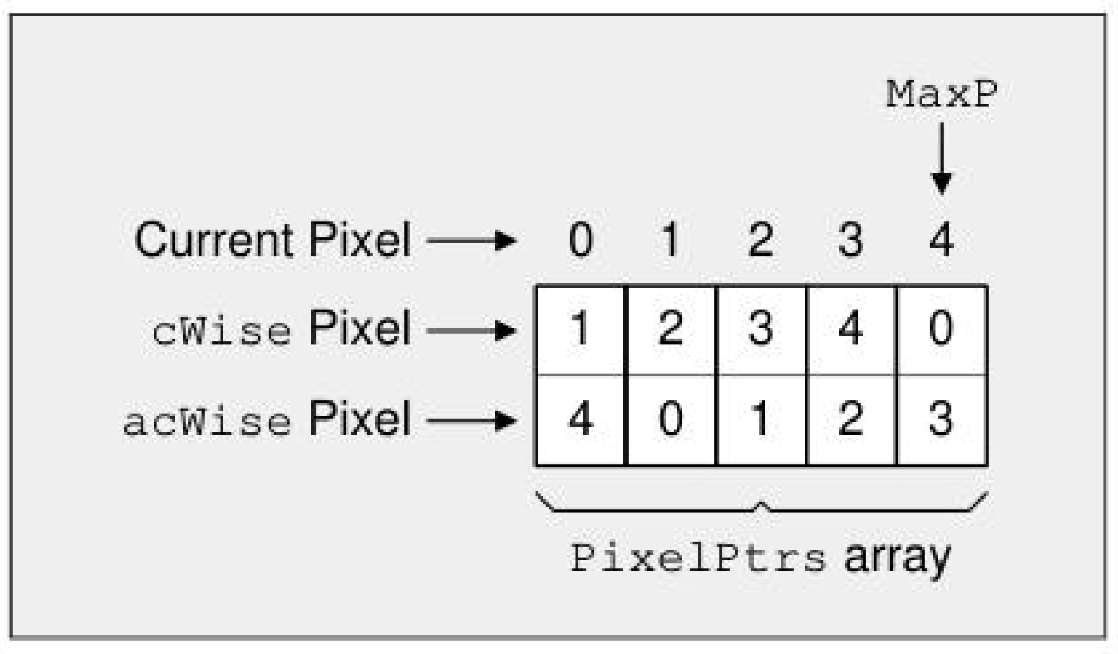
Now see if you can work out the equivalent solution for an anticlockwise rotation, and compare it to my version (**CB-Mar21-08.txt**).

Tortuous tables

Another pointer-based approach – still using our simplistic integer pointers as opposed to real C pointers – is to construct a look-up table in the form of an array whose size reflects the number of pixels we are playing with. We then load our table (array) with the calculated values for the adjacent clockwise (`cWise`) and anticlockwise (`acWise`) pixels (Fig.4).

Even though we are currently thought-experimenting with a 5-pixel ring, we want to make our implementation easily scalable to larger rings with more pixels. We'll start by taking our previous 'Chickens and eggs' clockwise rotation (file **CB-Mar21-07.txt**), spinning off a new version (file **CB-Mar21-09.txt**), and defining a structure called `CwAcwPair`, as shown below.

```
typedef struct
{
   int cWise;
   int acWise;
} CwAcwPair;
```



Current Pixel	0	1	2	3	4
cWise Pixel	1	2	3	4	0
acWise Pixel	4	0	1	2	3

Fig.4. Using a look-up table.

Remember that we introduced `typedef` (type definitions), `enum` (enumerated types), and `struct` (structures) in an earlier *Tips and Tricks* (*PE*, December 2020). Next, we are going to declare our look-up table as an array of these structures as follows:

```
CwAcwPair PixelPtrs[NUM_P];
```

Last, we will add a `for()` loop to our `setup()` function to load the `cWise` and `acWise` values into our `PixelPtrs[]` array as follows:

```
for (int iPix = 0; iPix < NUM_P; iPix++)
{
   PixelPtrs[iPix].cWise  = (iPix + 1) % NUM_P;
   PixelPtrs[iPix].acWise = (iPix + MAX_P) % NUM_P;
}
```

Observe that we are using exactly the same modulo-based operations to load this table that we used in our previous sketches. Based on this, we can rewrite our main `loop()` function as follows:

```
void loop ()
{
   // Turn old pixel off
   Neos.setPixelColor(CurrentP, COLOR_OFF);

   // Update the pointer
   CurrentP = PixelPtrs[CurrentP].cWise;

   // Turn new pixel on
   Neos.setPixelColor(CurrentP, COLOR_ON);

   // Display the result
   Neos.show();
   delay(PadDelay);
}
```

How about if we wish to modify this latest version of our program to perform an anticlockwise rotation? Nothing could be simpler. All we have to do is modify the pointer update statement in our main `loop()` to read as follows (file **CB-Mar21-10.txt**):

```
    CurrentP = PixelPtrs[CurrentP].acWise;
```

One disadvantage of using a table as we are doing here is that it consumes memory space, but so does any code we use to perform the same calculations multiple times. The advantages of the table approach are that we only perform our calculations one time and that the body of the program is easier to understand.

Now, you might say that, as part of our 'Chickens and eggs' discussions, we've already seen how to boil things down to a single calculation, but that's true only if we wish to turn an individual pixel off and another pixel on. If we were to opt for a more sophisticated effect, like a trailing fade that involves lighting the new pixel at 100% brightness and having the three trailing pixels set to 75%, 50%, and 25%, respectively, then we would find that this table-based approach makes our lives a lot easier.

Ah, `delay()`, I knew you well

In my column, *Is Time Truly an Illusion?* (**https://bit.ly/38mwa3k**), I posed the question: 'Did time exist before the Big Bang, was time an emergent property of the Big Bang, is time just something that keeps everything from happening at once, or does time as a fundamental property simply not exist at all?'

The reason I mention this here is that all of the programs we've looked at thus far have employed the `delay()` function to keep everything from happening at once. However, as we discussed in the *Dump the Delay* topic in a previous *Cool Beans* (*PE*, December 2020), the `delay()` is a blocking function, which means it completely ties up the processor, thereby preventing (or blocking) anything else from happening. While the processor is executing a `delay()`, it can't respond to changes on any of its inputs, it can't perform any calculations or make any decisions, and it can't change the state of any of its outputs.

One technique to replace the `delay()` is to cycle around checking the system clock to find when it's time to act. What we are going to do is take our table-based clockwise rotation program (**CB-Mar21-09.txt**) and modify it to use this new technique (file **CB-Mar21-11.txt**). As a result, our main `loop()` function will now be as follows:

```
void loop ()
{
   uint32_t currentTime = millis();

   // Is it time to do something?
   if ( (currentTime - TimeOfLastChange) >= PadDelay)
   {
      // Turn old pixel off
      Neos.setPixelColor(CurrentP, COLOR_OFF);

      // Update the pointer
      CurrentP = PixelPtrs[CurrentP].cWise;

      // Turn new pixel on
      Neos.setPixelColor(CurrentP, COLOR_ON);

      // Display the result
      Neos.show();

      TimeOfLastChange = currentTime;
   }
}
```

And, as before, if we wish to modify this latest version of our program to perform an anticlockwise rotation, then all we have to do is modify the pointer update statement in our main `loop()` to read as follows (file **CB-Mar21-12.txt**):

```
CurrentP = PixelPtrs[CurrentP].acWise;
```

And the winner is…

So, out of all of the techniques we've shown above – and remembering that there's more to come in this month's *Tips and Tricks* – which one is the best? Well, that's a bit like asking 'How long is a piece of string?'

In reality, it all depends on what we are attempting to achieve. If all we want to do is turn one pixel off and another one on, or vice versa, then we may opt for the solutions presented in the *Chickens and eggs* section. If we wish to add some slightly more sophisticated effects, then the programs provided in the *Tortuous tables* topic might offer the best option. Alternatively, if we want to be performing additional tasks while flashing our pixels – like checking the states of switches and performing complex calculations, for example – then the solutions offered in the *Ah, delay(), I knew you well* section would probably be the way to go.

What? No GOL?

I feel like an old fool (but where are we going to find one at this time of the day?). For the past two columns I've been promising to implement a version of Conway's *Game of Life* (*GOL*) (**https://bit.ly/pe-jan21-cgol**) on my 12x12 ping-pong-ball array.

Almost unbelievably, however, I allowed myself to become sidetracked once again (I'm as shocked as you). But dry those tears and start flaunting your happy face once again. Everything we've covered in this month's column regarding the use of the modulo operator is going to come into play when we implement the *GOL*, which we will do next month or my name's not Max the Magnificent! Until that frabjous day, as always, I welcome your comments, questions, and suggestions.

Cool bean Max Maxfield (Hawaiian shirt, on the right) is emperor of all he surveys at **CliveMaxfield.com** – the go-to site for the latest and greatest in technological geekdom.

Comments or questions? Email Max at: **max@CliveMaxfield.com**

Max's Cool Beans cunning coding tips and tricks

I'm quite excited as I start to pen these words because we are poised to gather a bunch of disparate concepts together and – at the end of this column – we are all going to say 'Wow!' (If you fail to say 'Wow!' with sufficient enthusiasm, I'll have to send my dear old mother to visit you to explain the error of your ways.)

Bits and bytes and nybbles, Oh my!

The smallest piece of information that can be stored and manipulated inside a digital computer is a binary digit (a.k.a. 'bit'), which can be used to embody two values. We typically think of these values as representing the numbers 0 and 1. As we discussed in my previous *Tips and Tricks* column (*PE*, February 2020), and assuming we are working with an Arduino microcontroller, these 0 and 1 values are equivalent to `LOW` and `HIGH`, respectively, when we are reading from or writing to the digital input/outputs (I/O). They are also equivalent to `false` and `true`, respectively, if we are treating them as Boolean logic values.

Since a single bit is limited with regard to the amount of information it can represent, we usually find it more convenient to work with groups of bits. Some groupings are common, so we've given them special names. For example, the term 'byte' refers to an 8-bit group, while the term 'nybble' (or 'nibble' – I prefer 'nybble'!) refers to a 4-bit group. This means that two nybbles make a byte, thereby demonstrating that computer engineers do have a sense of humor, albeit one that's not tremendously sophisticated.

Generally speaking, humans find it hard to wrap our brains around large numbers presented in binary. For example, 10101100 in binary doesn't mean much to most people, while its decimal equivalent of 172 is easier to comprehend.

The binary number system has two digits, 0 and 1. The decimal number system has 10 digits, 0, 1, 2, 3, 4, 5, 6, 7, 8, and 9. For reasons that will be made clear in future columns, mapping (translating) values back and forth between binary and decimal is not as convenient as one might hope. We find it much more efficacious to use the hexadecimal number system, which boasts 16 digits, 0, 1, 2, 3, 4, 5, 6, 7, 8, 9, A, B, C, D, E, and F. The beauty of this system is that each hexadecimal digit maps directly onto a 4-bit binary nybble (Fig.5.)

In previous *Tips and Tricks* columns (*PE*, August and September 2020) we discussed the difference between signed and unsigned integers. Also, the fact that in the case of the `int` (integer) data type, its size – ie, the number of bits used to represent it – depends on the computer you are working with. In the case of an Arduino Uno, for example, an `int` occupies two bytes (16 bits) of memory.

Let's suppose we declare an `int` called `intA`. Let's further suppose that we assign it a value of 0xCA35, where the '0x' prefix indicates that this is a hexadecimal value:

```
int intA = 0xCA35;
```

Using Fig.5 as a reference, we see that we've actually loaded `intA` with a binary value of 1100101000110101, as illustrated in Fig.6. Note that, rather than writing all 16 bits together in the form 1100101000110101, we may find it easier to think of them in terms of 4-bit nybbles and write them in the form 1100 1010 0011 0101 (this is what we will do in the remainder of this column).

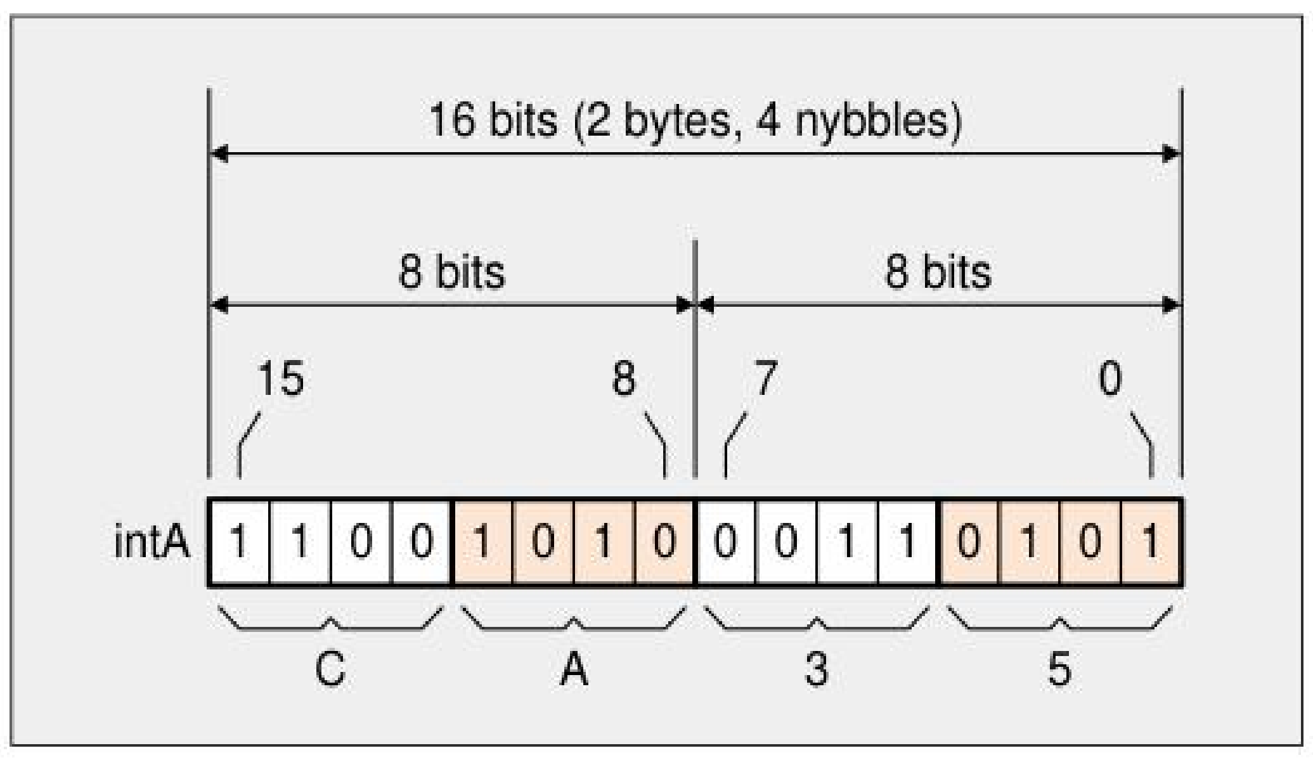


Fig.6. An example 16-bit value.

Decimal	Hexadecimal	Binary
0	0	0000
1	1	0001
2	2	0010
3	3	0011
4	4	0100
5	5	0101
6	6	0110
7	7	0111
8	8	1000
9	9	1001
10	A	1010
11	B	1011
12	C	1100
13	D	1101
14	E	1110
15	F	1111

Fig.5. Mapping binary and hexadecimal.

AND and OR gates

At its lowest level, a digital computer is composed of a humongous number of on/off switches. These switches can be implemented using a variety of technologies, including mechanical, electromechanical (relays), pneumatic, and semiconductors (transistors). These days, of course, transistors are all the rage – and that's what we will assume here – but who knows what may come tomorrow?

The next level up is to gather small groups of transistors and use them to implement simple logic functions – a.k.a. primitive logic gates – and to then connect these gates together in cunning ways. The two gates we will focus on in this column are the AND and OR gates (Fig.7).

Observe that we use the `&` character to represent the AND, while the | character is used to represent the OR. As we see, the output (`y`) from the AND gate is a 1 only if *both* of its inputs (`a` and `b`) are 1; otherwise, the output is 0. By comparison, the output of the OR gate is 1 if *either* of its inputs are 1.

The && and || logical operators

Previously, we were talking about AND and OR in the context of hardware; that is, the physical logic gates used to build the computer. Now we are going to consider related functions in software; that is, our programs.

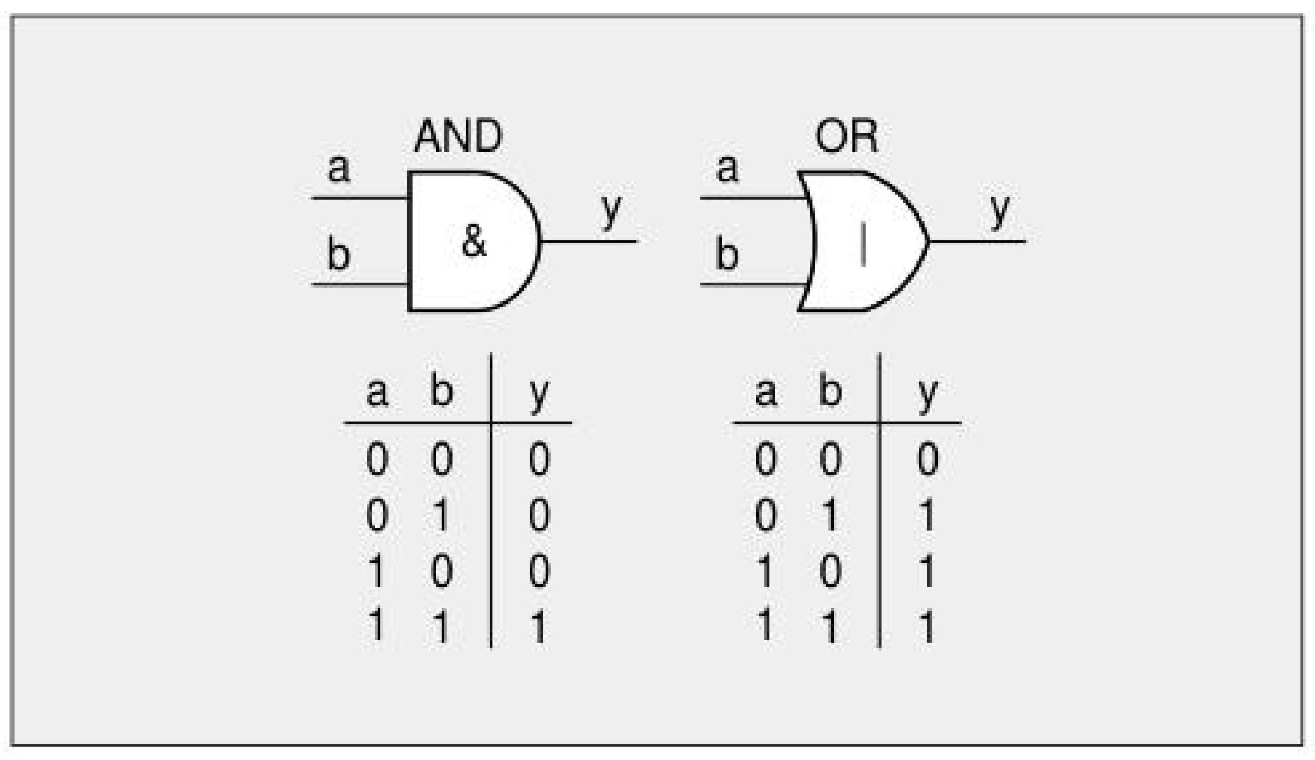
In last month's *Tips and Tricks* (*PE*, February 2021), we introduced the concept of Boolean variables, which can be assigned values of `false` and `true`. We also noted that these variables are often treated similar to integers in that `false` equates to 0 and `true` equates to 1 or – to be more precise – `true` equates to any non-zero value.

The `&&` and `||` logical operators allow us to construct complex conditional statements. For example, assuming that we've declared integer variables called `intA` and `intB`, we could write a test as follows:

```
if (((intA == 6) && (intB == 4)) == true)...
```

Note that we don't actually need all of the parentheses I've used here because the two == relational (comparison) operators on the left have a higher precedence than the `&&` logical AND operator, so we could have written this as follows:

```
if ((intA == 6 && intB == 4) == true)...
```



a	b	y
0	0	0
0	1	0
1	0	0
1	1	1

a	b	y
0	0	0
0	1	1
1	0	1
1	1	1

Fig.7. AND and OR gates.

However, if you aren't sure about operator precedence (**https://bit.ly/355G9rC**), then it's always best to use parentheses to force things to happen in the order you want them to, with the added advantage that parentheses usually make it easier for other people to work out what you are trying to achieve.

Let's think about how the above expression will be evaluated by the compiler, and therefore how it will be executed by the computer. If `intA` is equal to 6, then this sub-expression will return `true` (1), otherwise it will return `false` (0). Similarly, if `intB` is equal to 4, then this sub-expression will return `true` (1), otherwise it will return `false` (0). The `&&` operator will only return `true` (1) if both of its inputs are `true` (1), otherwise it will return `false` (0). Finally, we use the rightmost == operator to compare the result from the `&&` to a value of `true` (1). Once again, this comparison will only return a value of `true` (1) if both of its inputs are `true` (1), otherwise it will return `false` (0).

Actually, a little thought reveals we can simplify this test by writing it as follows:

```
if ((intA == 6) && (intB == 4))...
```

Although we are in danger of wandering off into the weeds, a little more thought reveals that – assuming we've also declared an integer variable called `intY` – the following would also be a valid statement:

```
intY = intA && intB;
```

In this case, if `intA` contains 0, the `&&` operator will regard it as being `false` (0); otherwise, if `intA` contains a non-zero value, the `&&` operator will regard it as being `true` (1). Similarly, for `intB`. As a result, the `&&` operator will return `true` (1) only if both `intA` and `intB` contain non-zero values; otherwise, it will return `false` (0). And whatever value is returned from the `&&` operator will be assigned to `intY`.

We can think of the `&&` logical operator as being a giant software AND (Fig.8a); similarly, we can think of the `||` logical operator as being a giant software OR (Fig.8b).

The & and | bitwise operators

When we are writing programs, we can also use the `&` (bitwise AND) and `|` (bitwise OR) operators. The bitwise AND accepts two integer values as inputs and performs an AND on each pair of corresponding bits. In the computer, this is actually implemented using a bunch of physical AND gates. Similarly, the bitwise OR operator uses a bunch of physical OR gates to perform an OR on each pair of corresponding bits.

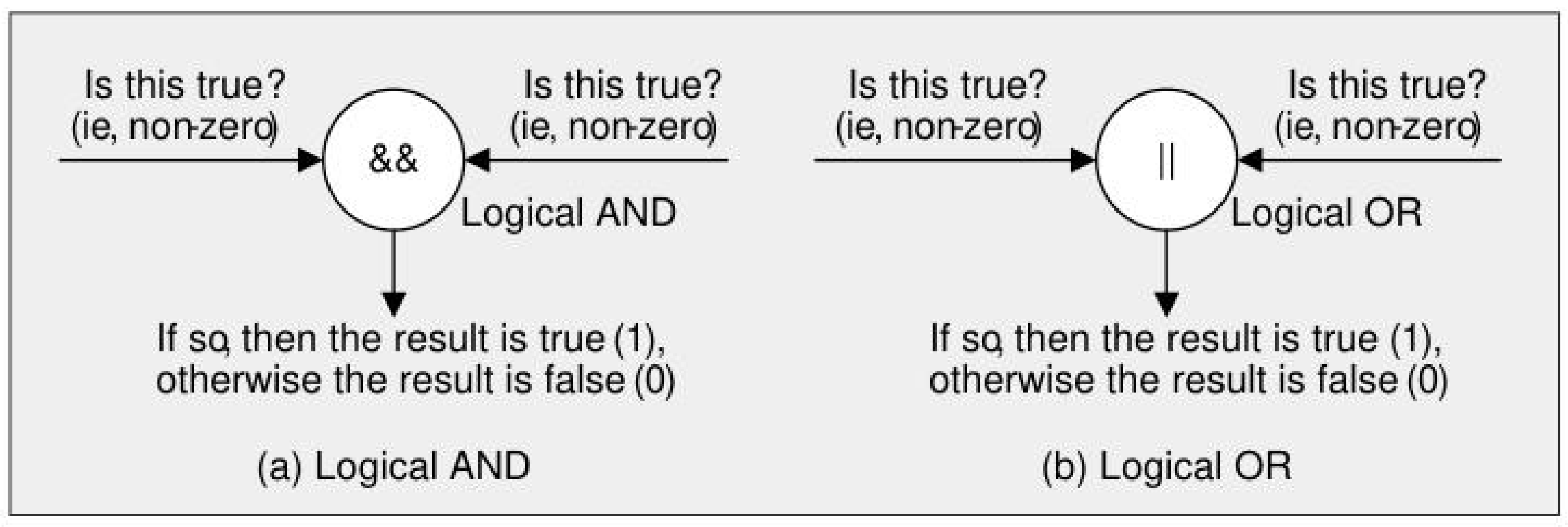

Is this true?
(ie, non-zero)
&&
Is this true?
(ie, non-zero)
Logical AND
If so, then the result is true (1),
otherwise the result is false (0)
(a) Logical AND
Is this true?
(ie, non-zero)
||
Is this true?
(ie, non-zero)
Logical OR
If so, then the result is true (1),
otherwise the result is false (0)
(b) Logical OR

Fig.8. Visualising the `&&` and `||` logical operators.

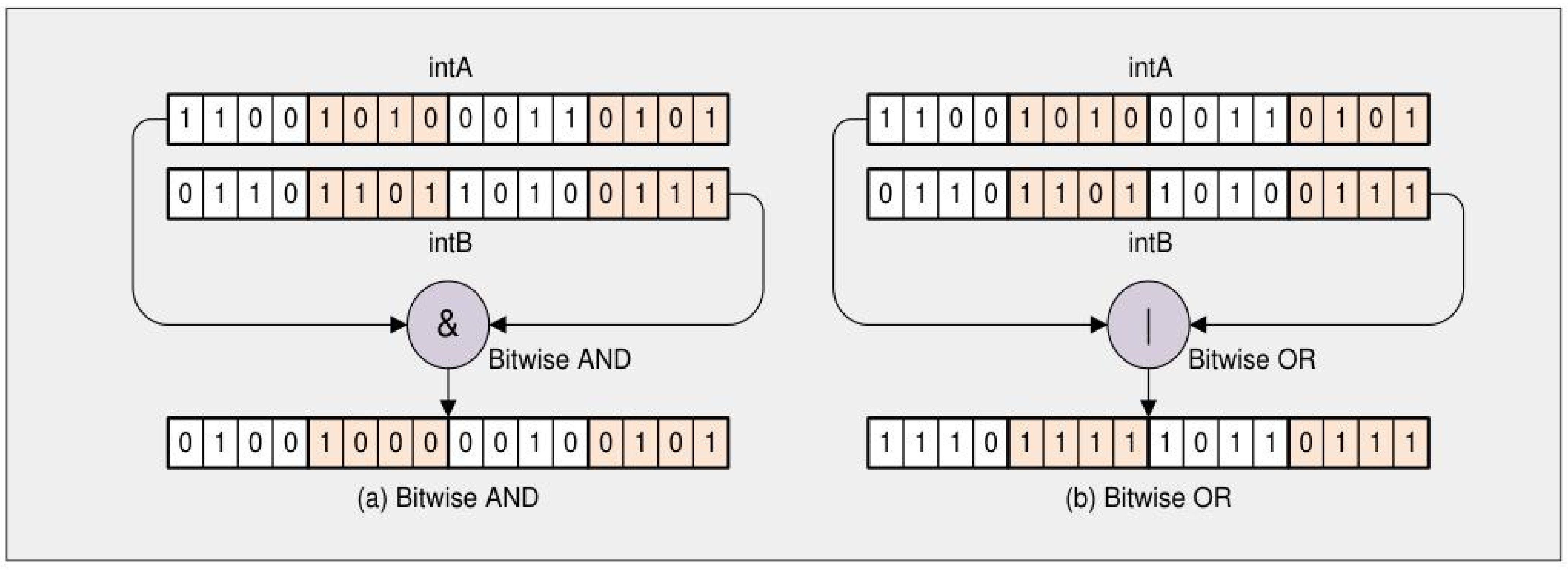

intA
1 1 0 0 1 0 1 0 0 0 1 1 0 1 0 1
0 1 1 0 1 1 0 1 1 0 1 0 0 1 1 1
intB
&
Bitwise AND
0 1 0 0 1 0 0 0 0 0 1 0 0 1 0 1
(a) Bitwise AND
intA
1 1 0 0 1 0 1 0 0 0 1 1 0 1 0 1
0 1 1 0 1 1 0 1 1 0 1 0 0 1 1 1
intB
|
Bitwise OR
1 1 1 0 1 1 1 1 1 0 1 1 0 1 1 1
(b) Bitwise OR

Fig.9. Visualising the `&` and `|` bitwise operators.

Assume that we declare three integers, `intA`, `intB`, and `intY`. Remember that we are also assuming that we are working with an Arduino Uno, so each of these integers will be two bytes (16 bits) wide. Suppose we assign a value of 0xCA35 in hexadecimal (1100 1010 0011 0101 in binary) to `intA` and a value of 0x6DA7 in hexadecimal (0110 1101 1010 0111 in binary) to `intB`. Now suppose we use the following statement in our program to perform a bitwise AND:

```
intY = intA & intB;
```

The least significant bit of `intA` is 1, as is the least significant bit of `intB`, so an AND of these means the least significant bit of the result will also be a 1. Similar operations are performed for all of the other bits (Fig.9a), resulting in `intY` containing 0x4825 in hexadecimal (0100 1000 0010 0101 in binary).

Now assume that we start with `intA` and `intB` containing the same values as before and we use the following statement in our program to perform a bitwise OR:

```
intY = intA | intB;
```

In this case, we perform an OR operation on each pair of corresponding bits (Fig.9b), resulting in `intY` containing 0xEFB7 in hexadecimal (1110 1111 1011 0111 in binary).

Testing bits

Suppose we know that `intA` currently contains a valid value, but we don't actually know what this value is. Purely for the purpose of these discussions, we could visualise this as 0x???? in hexadecimal (???? ???? ???? ???? in binary). Now suppose that we wish to perform a test to determine if bit 7 of `intA` is a 1 and, if so, perform some actions. We could achieve this using the bitwise AND operator and a reference value of 0x0080 (0000 0000 1000 0000) as follows:

```
if ((intA & 0x0080) == true)...
```

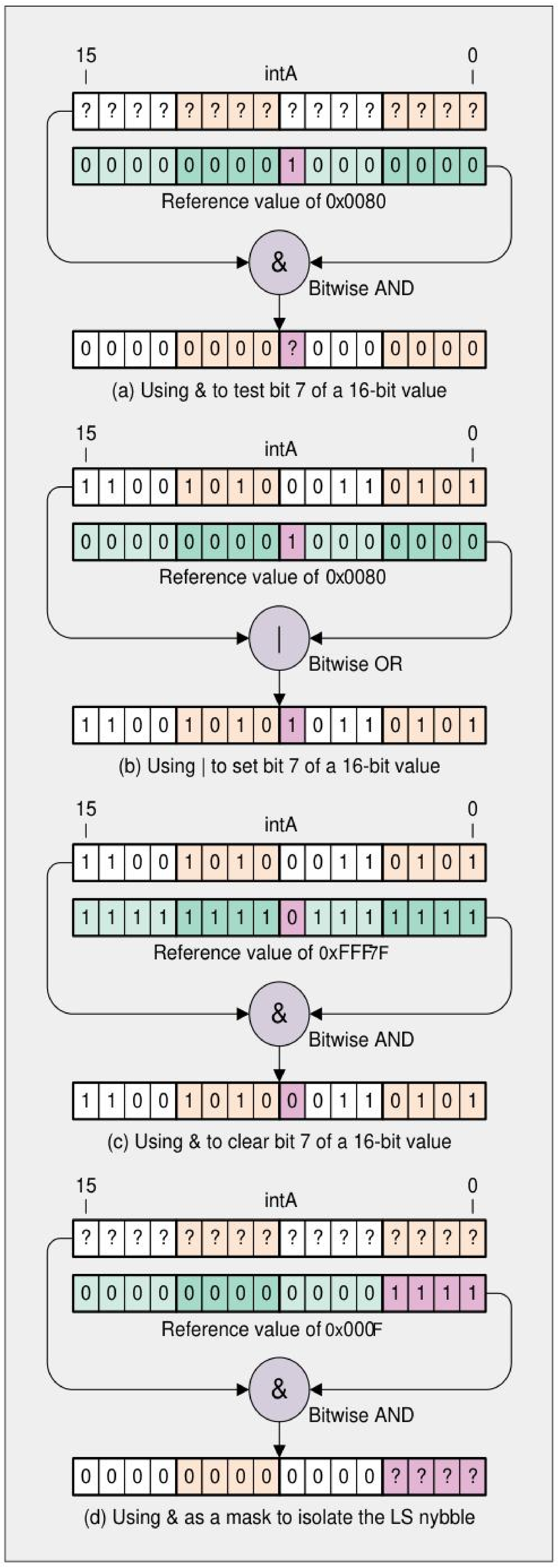

15
intA
0
? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ?
0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0
Reference value of 0x0080
&
Bitwise AND
0 0 0 0 0 0 0 0 ? 0 0 0 0 0 0 0
(a) Using & to test bit 7 of a 16-bit value
15
intA
0
1 1 0 0 1 0 1 0 0 0 1 1 0 1 0 1
0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0
Reference value of 0x0080
|
Bitwise OR
1 1 0 0 1 0 1 0 1 0 1 1 0 1 0 1
(b) Using | to set bit 7 of a 16-bit value
15
intA
0
1 1 0 0 1 0 1 0 0 0 1 1 0 1 0 1
1 1 1 1 1 1 1 1 0 1 1 1 1 1 1 1
Reference value of 0xFF7F
&
Bitwise AND
1 1 0 0 1 0 1 0 0 0 1 1 0 1 0 1
(c) Using & to clear bit 7 of a 16-bit value
15
intA
0
? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ?
0 0 0 0 0 0 0 0 0 0 0 0 1 1 1 1
Reference value of 0x000F
&
Bitwise AND
0 0 0 0 0 0 0 0 0 0 0 0 ? ? ? ?
(d) Using & as a mask to isolate the LS nybble

Fig.10. Testing, setting, clearing, and masking bits.

A graphical representation of this operation is shown in Fig.10a. For every bit that is 0 in the reference value, the corresponding output bit from the bitwise AND is forced to 0. Since bit 7 in the reference value is 1, the corresponding output bit will reflect the value of bit 7 in `intA`.

If bit 7 in `intA` is 0, the value returned from `(intA & 0x0080)` will be zero, which is considered to be `false`, so our test will boil down to if `(false == true)`. Obviously, this will fail, and the statements encompassed by the `if()` will not be executed.

Alternatively, if bit 7 in `intA` is 1, the value returned from `(intA & 0x0080)` will be 0x0080 – that is, non-zero – which is considered to be `true`, so the test will boil down to if `(true == true)`. Obviously, this will pass, and the statements encompassed by the `if()` will therefore be executed.

From our earlier discussions, we know that we could achieve the same effect using the following statement:

```
if (intA & 0x0080)...
```

Now suppose that we wish to perform the actions encompassed by the `if()` only if bit 7 of `intA` contains a 0. In this case, we could use the following statement:

```
if ((intA & 0x0080) == false)...
```

Alternatively, we could achieve the same effect as follows:

```
if (!(intA & 0x0080))...
```

We can read this latter version as 'If not `(intA & 0x0080)` then...' or 'If the bitwise AND of `intA` and 0x0080 doesn't return a true (non-zero) value, then…' I know that this can be a tad confusing at first, but it won't be long before you can read and write this sort of thing without thinking (too hard) about it.

Setting and clearing bits

Let's suppose that `intA` contains some value like 0xCA35 (1100 1010 0011 0101) and we wish to set its bit 7 to 1 while leaving its other bits unchanged. We could achieve this using the bitwise OR operator and a reference value of 0x0080 (0000 0000 1000 0000) as follows.

```
intA = intA | 0x0080;
```

As illustrated in Fig.10b, the result is to leave `intA` containing 0xCA**B**5 (1100 1010 **1**011 0101). Now suppose that we change our minds, and we decide that we really want to clear bit 7 of `intA` to 0 while, once again, leaving the other bits unchanged. We could achieve this using the bitwise AND operator and a reference value of 0xFF7F (1111 1111 0111 1111) as follows.

```
intA = intA & 0xFF7F;
```

As illustrated in Fig.10c, the result, in this case, is to leave `intA` containing 0xCA**3**5 (1100 1010 **0**011 0101).

Masking bits

As you will see, this is a logical extension of what we've seen before. As we did while testing bits, let's suppose that we know that `intA` currently contains a valid value, but that we don't actually know what this value is, so we will visualise this as 0x???? in hexadecimal (???? ???? ???? ???? in binary). Now suppose that we wish to 'extract' only the least-significant nybble and copy this into `intY`. We could achieve this as follows (Fig.10d):

```
intY = intA & 0x000F;
```

As a reminder, we used various combinations of masks and shifts to extract the three 8-bit red, green, and blue channels from a 32-bit color value (the most significant 8 bits aren't used) in an earlier *Cool Beans* column (*PE*, October 2020). So, why are masking operations of interest to us here? Well, I'm glad you asked...

Just call me 'Lord of the Rings'

Returning to the rings of LEDs we've been discussing in our *Cool Beans* columns, when it comes to rotating a pixel around the ring, there's a trick we can use if the number of pixels in the ring is a power of two. In the case of my *Prognostication Engine* project, for example, the rings each have 16 pixels, where $16 = 2^4$. As we know, these pixels are numbered from 0 in decimal (0 in hexadecimal; 0000 in binary) to 15 in decimal (F in hexadecimal; 1111 in binary).

Cast your mind back to the *Chickens and eggs* topic in this month's *Cool Beans* column. Suppose we wished to employ this approach with the *Prognostication Engine's* 16-pixel rings. With our newfound knowledge of masks, when it comes to incrementing the pointer in our clockwise rotation (file **CB-Mar21-07.txt**), we could replace the original modulo calculation `(CurrentP = (CurrentP + 1) % NUM_P;)` in our main `loop()` function with a masking operation as follows (the modified portion is shown in bold):

```
void loop ()
{
   // Turn old pixel off
   Neos.setPixelColor(RingXref[CurrentP], COLOR_OFF);

   // Increment the pointer
   CurrentP = (CurrentP + 1) & MAX_P;

   // Turn new pixel on
   Neos.setPixelColor(RingXref[CurrentP], COLOR_ON);

   // Display the result
   Neos.show();
   delay(PadDelay);
}
```

How does this work? Well, if you look at my source code (file **CB-Mar21-13.txt**), you'll see that we've defined `NUM_P` as 16. Since `MAX_P` is defined as `(NUM_P - 1)`, this means that `MAX_P` is 15 in decimal (F in hexadecimal; 1111 in binary).

For `CurrentP` equals 0 to `CurrentP` equals 14, `(CurrentP + 1)` will equal 1 to 15, respectively. In the context of our 16-bit integers, this corresponds to `(CurrentP + 1)` values of 0x0001 to 0x000F in hexadecimal, or 0000 0000 0000 0001 to 0000 0000 0000 1111 in binary. If we use the bitwise AND operator to perform a mask operation on these values with a reference value of `MAX_P`, which will be automatically promoted to 0x000F (0000 0000 0000 1111), then they will all pass through unscathed.

Now consider what happens when `CurrentP` equals 15, which means `(CurrentP + 1)` will equal 16 in decimal (0x0010 in hexadecimal; 0000 0000 0001 0000 in binary). In this case, our bitwise AND will mask out the three most-significant nybbles and return 0. As a result, our count progresses from 0 to 15 and then returns to 0 again, which is just what we want.

As an aside, you may have noticed that whenever we call the `Neos.setPixelColor()` function in the above code snippet, instead of the first argument being `CurrentP`, we've changed this to be `RingXref[CurrentP]`.The reason for this is that, as discussed in a previous *Cool Beans* column (*PE*, January 2021), the physical pixels on the 16-element ring in my prototype aren't oriented and connected the way we want them to be, so we use the `RingXref[]` array to translate what we have in our virtual world (in the form of `CurrentP`) into what we need in the real world.

Finally, let's consider using the mask technique for an anticlockwise rotation. Before we proceed, let's remind ourselves that an integer in a computer occupies a limited number of bits (16 in the case of an Arduino Uno). So, what happens if our integer already contains 0xFFFF (1111 1111 1111 1111) and we add 1 to this? The result is an overflow condition where the integer ends up containing 0x0000 (0000 0000 0000 0000). Contrawise, if our integer contains 0x0000 (0000 0000 0000 0000) and we subtract 1, we get an underflow condition leaving the integer containing 0xFFFF (1111 1111 1111 1111).

Now consider the new implementation of our anticlockwise rotation (file **CB-Mar21-14.txt**) and compare it to our original implementation (file **CB-Mar21-08.txt**). In this case, we can replace the original modulo calculation `(CurrentP = (CurrentP + MAX_P) % NUM_P;)` in our main loop() function with a masking operation as follows (the modified portion is shown in bold):

```
void loop ()
{
   // Turn old pixel off
   Neos.setPixelColor(RingXref[CurrentP], COLOR_OFF);

   // Decrement the pointer
   CurrentP = (CurrentP - 1) & MAX_P;

   // Turn new pixel on
   Neos.setPixelColor(RingXref[CurrentP], COLOR_ON);

   // Display the result
   Neos.show();
   delay(PadDelay);
}
```

If you compare this to our clockwise version, you'll see that all we've done is change the '+' to a '–'. So, how does this one work?

Well, for `CurrentP` equals 15 to `CurrentP` equals 1, `(CurrentP - 1)` will equal 14 to 0, respectively. This corresponds to `(CurrentP - 1)` values of 0x000E to 0x0000 in hexadecimal, or 0000 0000 0000 1110 to 0000 0000 0000 0000 in binary. As before, our bitwise AND mask operation will pass all of these values through unscathed.

Now consider what happens when `CurrentP` equals 0, which means `(CurrentP - 1)` will equal 0xFFFF in hexadecimal; 1111 1111 1111 1111 in binary. In this case, when our bitwise AND masks out the three most-significant nybbles, the result will be 0x000F (0000 0000 0000 1111), which is 15 in decimal. As a result, our count progresses from 15 down to 0 and then returns to 15 again, which is what we are looking for.

The advantage of the mask approach is that, in the case of a simple microcontroller, replacing a modulo division with a simple bitwise AND can potentially save a bunch of clock cycles. The disadvantage is that the modulo approach works with rings containing an arbitrary number of pixels, while the mask technique works only if the number of pixels is a power of two.

What say you?

Phew! We've certainly covered a lot of ground this month, but I hope you've found these discussions to be both interesting and useful. As always, I welcome your comments, questions, and suggestions.

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AUDIO OUT

By Jake Rothman

Making a Transistor Radio – Part 1

Nearly 50 years ago I tried to build a radio. I was young, inexperienced… and it didn't work. I wasn't the only one to try. In fact, it must be one of the most popular radio projects ever printed, but the strange thing is it didn't appear in any of the regular radio or electronics magazines – it wasn't even aimed at adults. It appeared in a massively popular and influential series of children's books called 'Ladybird'. (If you have a little time to spare then there is a very pleasant (non-electronic) hour to be spent watching this documentary: **http://bit.ly/pe-mar21-lb**).

48 years to get it working

All these years later that early failure to finish the project bugged me, and this project will set that right! In fact, not only will we build the complete original version of the *Ladybird Radio*, but also I have a few upgrades to suggest. First though, a little background.

The idiosyncratic serious-amateur culture here in the UK makes the country's art and technology output surpass its economic size. Maybe this was because it was the cradle of the Industrial Revolution, but I suspect the plethora of electronics magazines and books were a major factor. Among these, were the Ladybird series of children's illustrated books, and some of my collection is shown in Fig.1.

THE COMPUTER
LIGHT, MIRRORS and LENSES
THE ROCKET
THE LOCOMOTIVE
The story of RADIO
Learnabout… Woodwork
THE STORY OF Metals
THE CAMERA
Metalwork
TELEVISION

Fig.1. A small sample of the famous Ladybird books.

Life begins and ends

I suspect for many of us, an engineering or science career really starts around the age of ten. For me, that was 1972, the year the Reverend George Dobbs' Ladybird Book *Making a Transistor Radio* came out – shown in Fig.2. It even helped me learn to read, since nothing else at school captured my interest.

This book entered the Children's Top Ten for a while and influenced a generation of youngsters. Unfortunately, I never got to meet George Dobbs. I was hoping to interview him about his book at the 2018 Welsh Radio Rally at Newport in October 2018, but he was ill and cancelled his lecture. He died shortly afterwards aged 75 in March 2019. (*Practical Wireless* magazine, however, did interview him in their June 2009 issue.)

Old shops

Luckily, I found that one of my component suppliers, John Birkett's of Lincoln, had known George as a family friend for more than 50 years. John's shop was established in 1962, and is one of the last bricks-and-mortar stores remaining, along with a few others, such as Cricklewood Electronics and JPR. He still has some of George's books and supplies all the old components for those wishing to build the *Ladybird Radio* and vintage electronic equipment. John is now in his nineties, so today the shop is mainly run by his daughter Judy, who incidentally was christened by Rev Dobbs. There is an interview with them both in the Jan 2020 issue of *Practical Wireless*.

Finding copies today

Making a Transistor Radio has long been out of print, but you might strike lucky at a boot fair or charity shop and pay 50p. Of course, eBayers may have got there before you. On the Net they can cost up to £20 for a clean early edition, but the average cost is around £5-8, even though they often say '15p' on the back! A little Googling will probably enable you to find an online version.

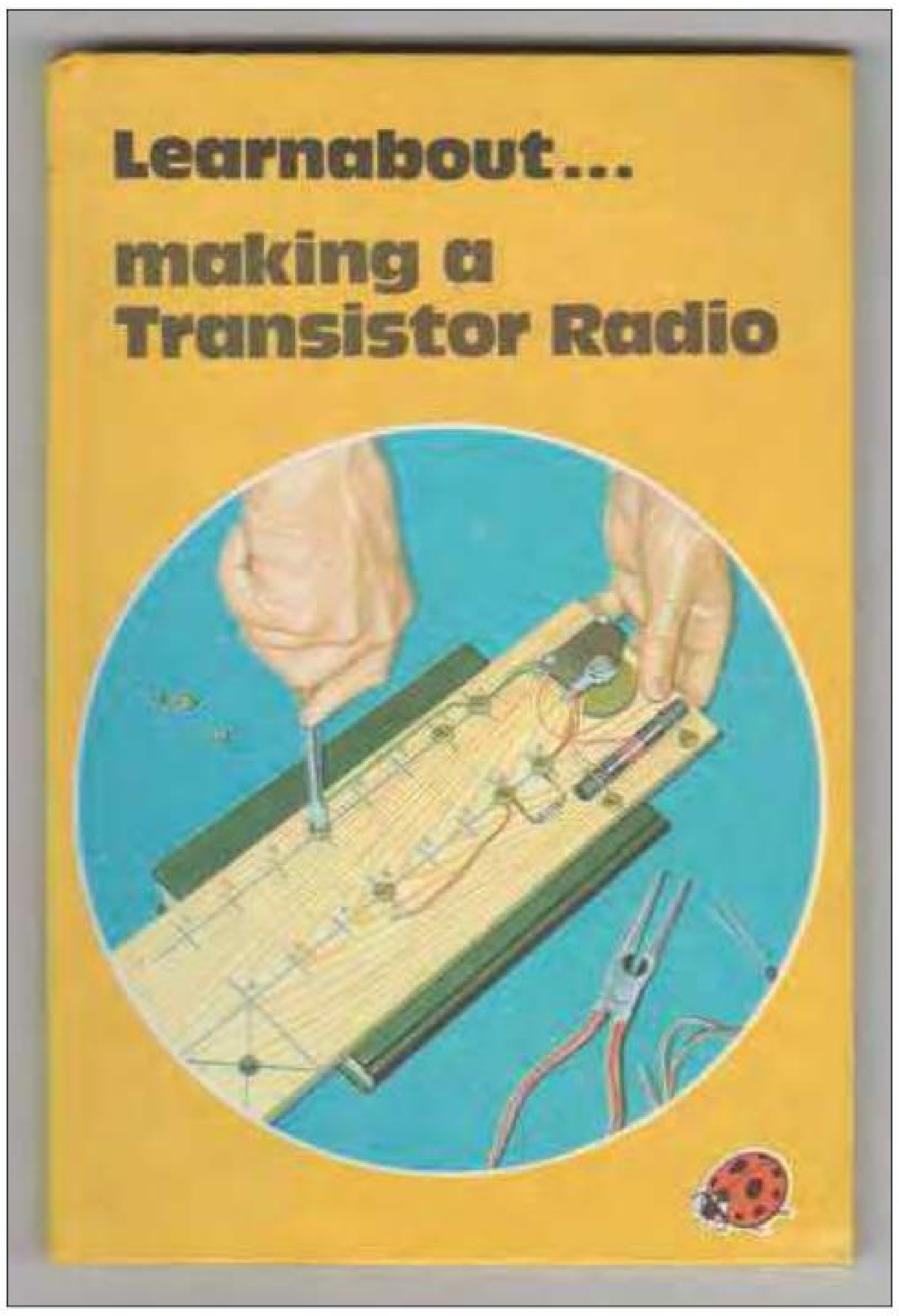

Fig.2. *Making a Transistor Radio*, an influence on many of *PE's* older readers?

Look Mum! – No Computer!

There were many brilliant beginner's technology books in the Ladybird series. The books were 'The Internet' of my childhood. They introduced my 'plastic' mind to all forms of technology.

I migrated from the Ladybird books to Hamlyn Publishing's colour paperbacks, because they were visual rather than the algebraic nature of most technical books. *Electronics*, written by Roland Worcester (a pseudonym of FG Rayer who wrote many articles for 1970s electronic magazines) was a favourite. It had fantastic colour circuit diagrams, and since no one collects these books they are going for junk prices (I give them to students). Next, I started soldering at age 11, sat on the floor and wiping my Antex iron on my mother's white carpet. (A mistake I was advised to make only once!)

Electronic art

Just as in botany and anatomy books, the concepts and construction in the Ladybird and Hamlyn series were explained

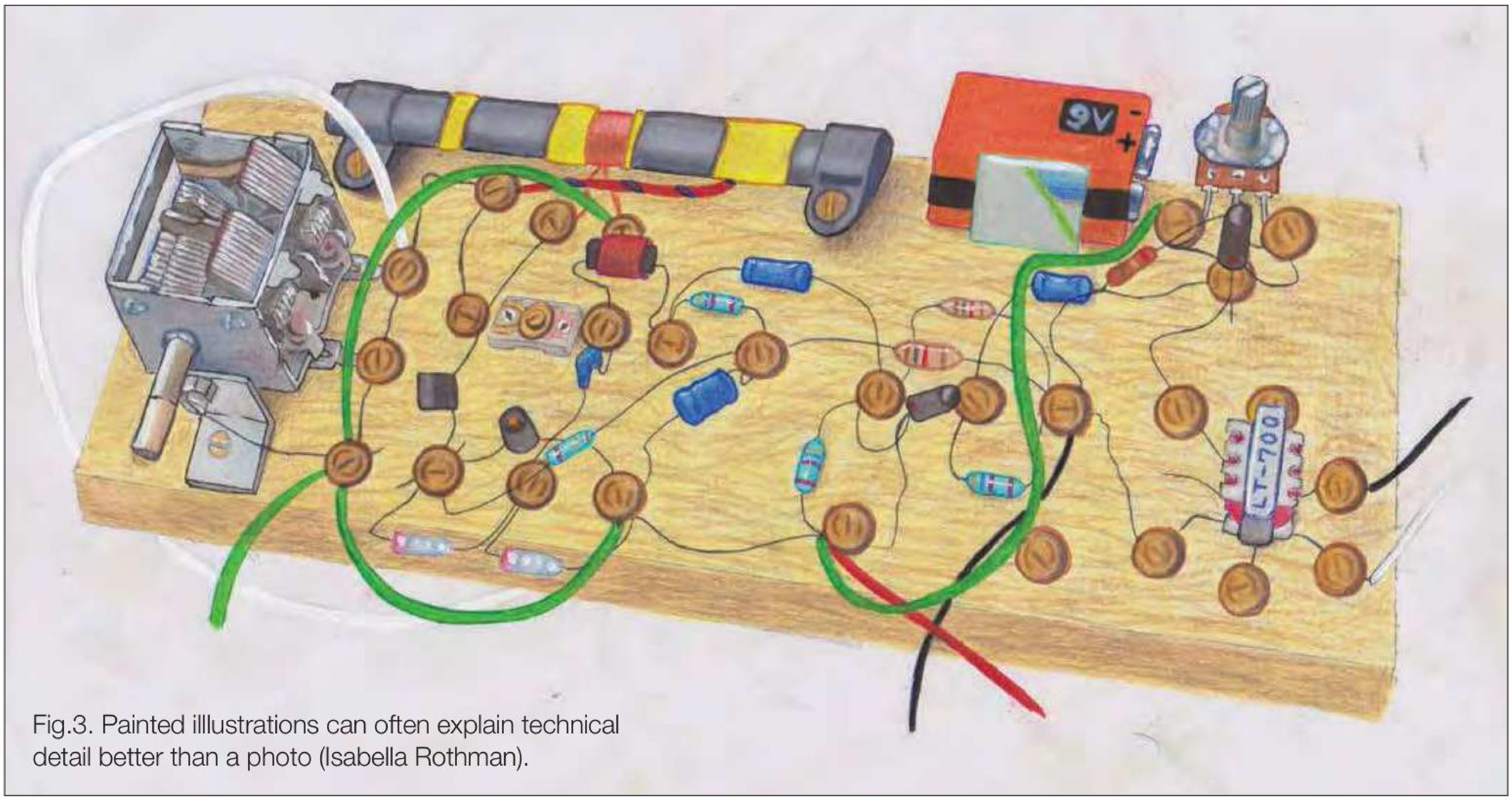

Fig.3. Painted illustrations can often explain technical detail better than a photo (Isabella Rothman).

with illustrations – not photographs. These are clearer than photos because the main points can be emphasised and redundant information omitted. One of my neighbours was an illustrator for the Ladybird *Peter and Jane* series, sadly she didn't do the radio illustrations, that was Bernard Robinson – see: **http://bit.ly/pe-mar21-lb1**

Bernard was my favourite Ladybird illustrators, and he was especially interested in music and technology. We can't use the Ladybird Book illustrations here because Penguin owns the copyright, but my daughter Isabella has drawn a similar example in Fig.3. Long may she continue the tradition!

Real breadboarding

Even in the 'Supersonic Seventies', the publishers considered soldering to be too dangerous for children, so George came up with a unique construction system using brass screws and cups. This involved clamping the wires down on a piece of wood to make the connections, resulting in a genuine breadboard, as shown in Fig.4. There was one problem with this technique, you had to be physically strong enough to do the woodwork. I got nowhere on my first attempts because I used hardwood – for a child to drive screws into wood it has to be a softwood, such as pine. Drilling recesses for pot nuts with a brace-and-bit was also difficult; I went all the way through on my first attempt. If only I'd had a Makita power screwdriver/drill in those days! 2mm pilot holes are much better than a bradawl for starting screws.

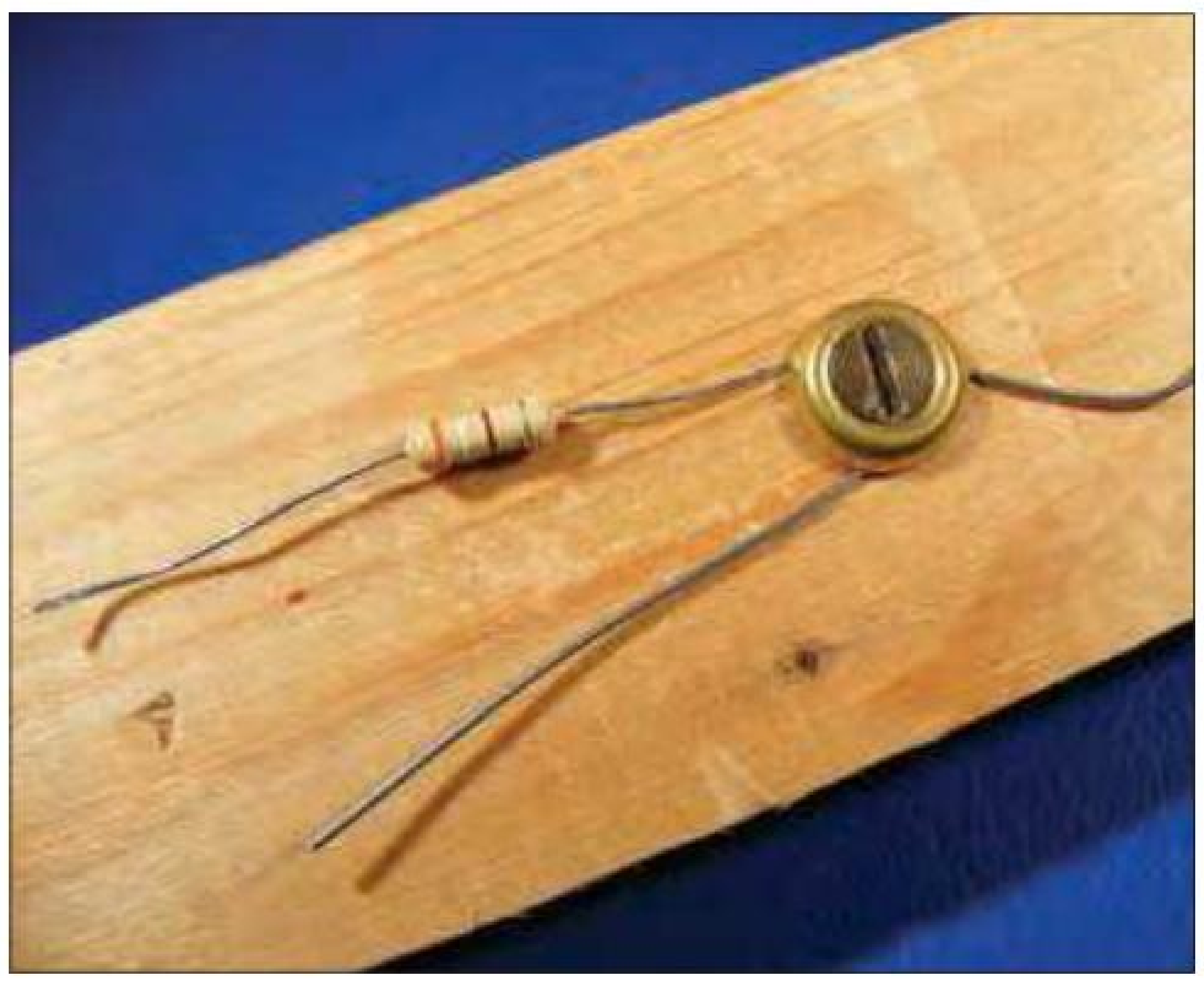

Fig.4. George Dobbs' screw-and-cup connection technique.

I then asked my mother to buy me the Ladybird woodwork and metalwork books from the Manchester bookshop where she worked. In turn, I have used these books to teach the same skills to my children.

The strange thing is, after a day of employing the screw-and-cup technique I got used to it. I now use it in areas of solderless prototyping, such as connecting large components to modern breadboards and passive loudspeaker crossovers. The screws do need periodic re-tightening, however. Also, a combination of wires of different diameters under the same cup can result in the thinnest wire, such as from a transistor coming loose.

Conductive wood

When we get to the construction stage, beware of slightly green-tinged pieces of wood used for fencing and decking. These are tanalised to prevent rot, a process that impregnates the wood with copper compounds, even arsenic was used in the US until 2003. This means the wood is useless for 'bread-boarding' because it becomes mildly electrically conductive when damp. The resistance can drop to about 250kΩ between probes, as shown in Fig.5. With the large surface area of the Ladybird 'breadboard/screw' technique it gets much lower. Fortunately, germanium transistor circuits are generally low impedance, so most (non-treated) wood is fine. I used 9mm plywood.

Today, I suspect a new children's construction technique would use 'choc-blocks'. However, that would lack the unique visual clarity of the Ladybird method.

Getting it done… eventually

I'm sad to say my first *Ladybird Radio* never worked. It didn't put me off though, because I just knew electronics was what I wanted to do. I did get the wooden multivibrator working in Dobbs' second Ladybird book, *Learn about… Simple Electronics*. I still use this circuit to introduce electronics to my students.

I know we all have 'skeleton projects in our closets'; but this one, at 48-years late was my worst, so I decided to have another go at the radio to see what went wrong. Was it 'bad' wood – or me? I started with the book's first circuit, the crystal set.

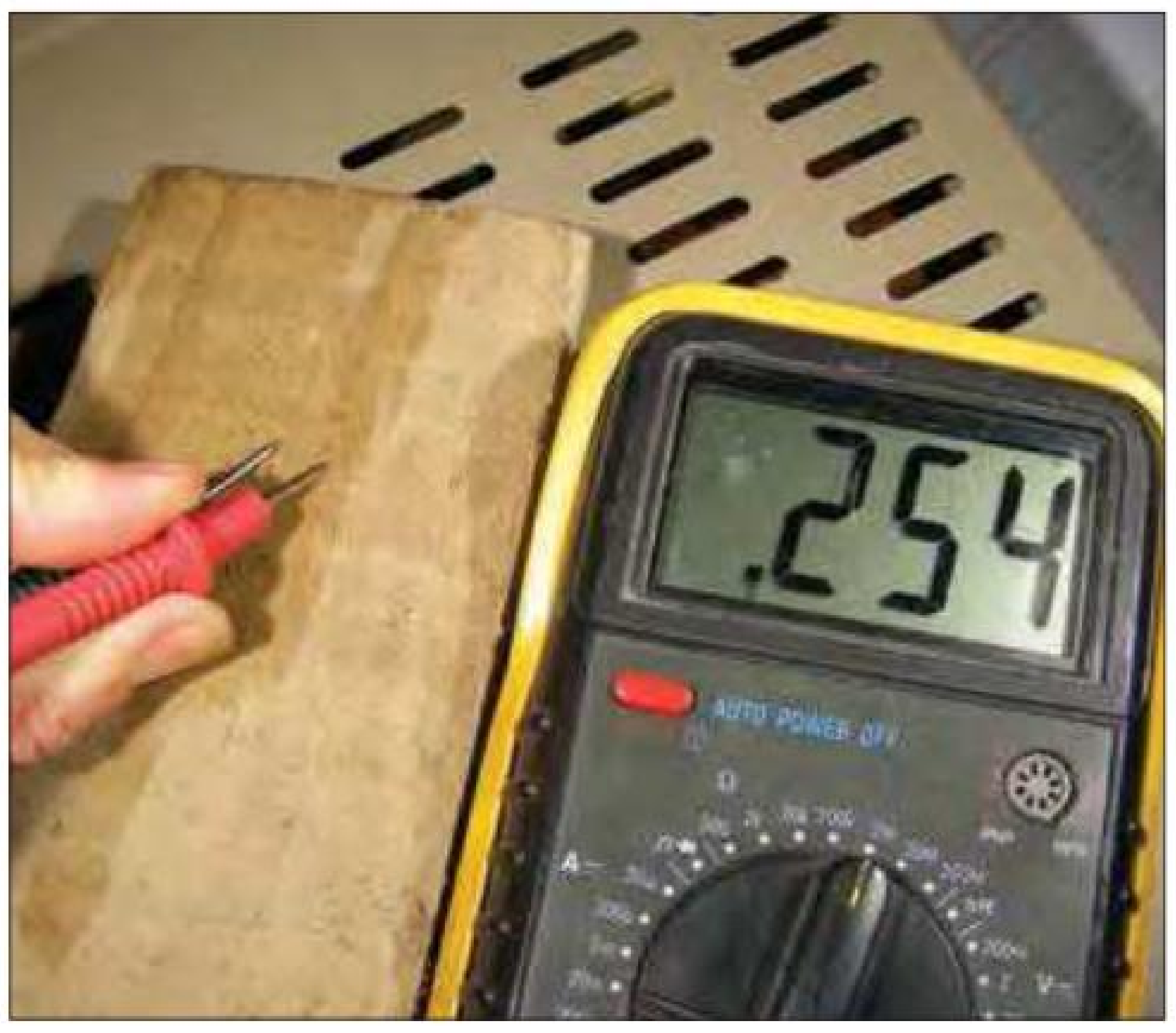

Fig.5. Tanalised wood can be conductive – do not use it in this project.

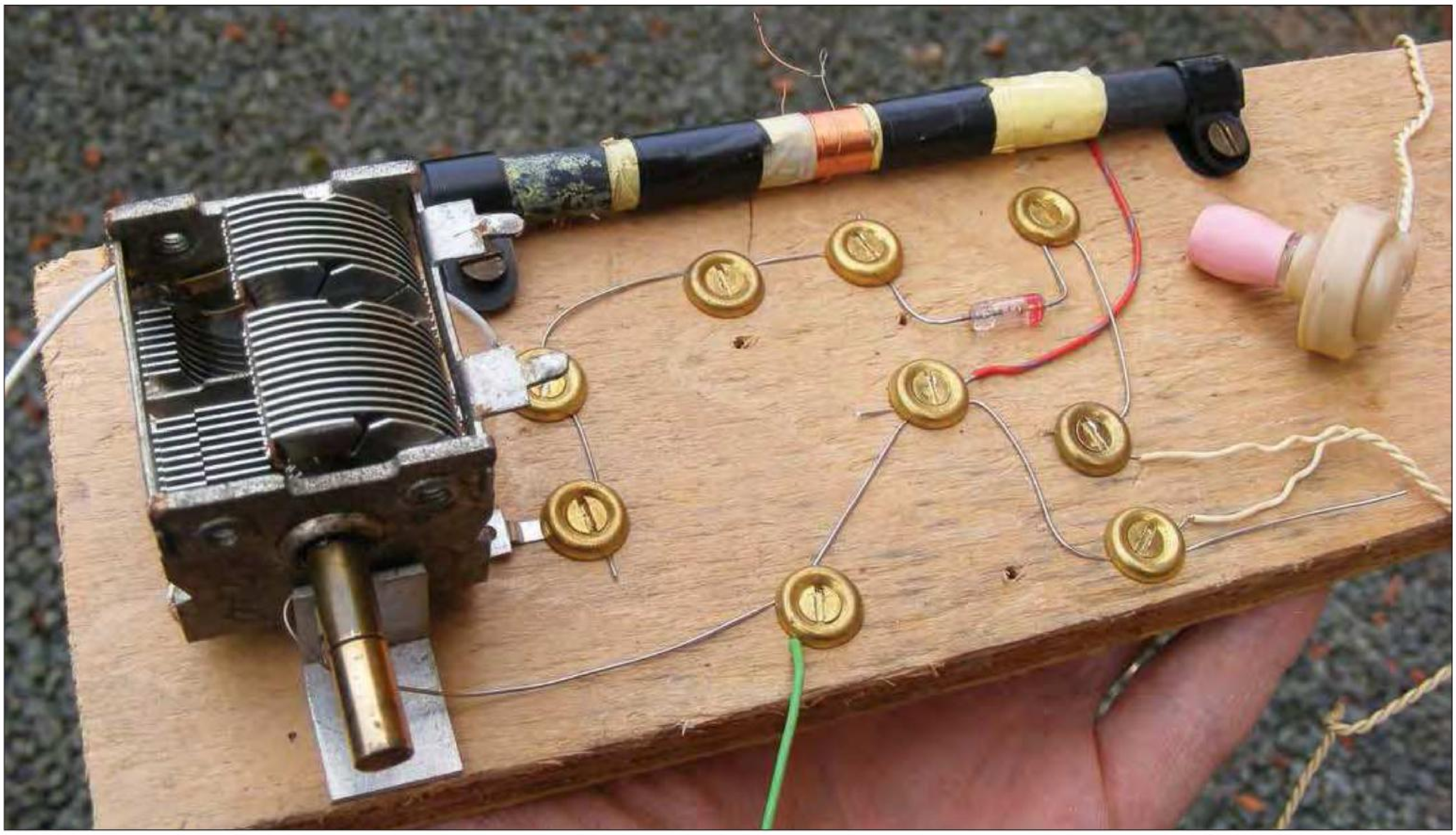

Fig.6. The simplest radio – a crystal set, and the first design in the Ladybird book. Note the OA70 glass diode, centre right.

Crystal set

The simplest radio construction is a crystal set, shown in Fig.6. It is completely passive and needs no battery, using the radio wave energy itself. Of course, crystal sets only receive 'old-fashioned' amplitude modulated (AM) transmissions, such as BBC Radio 4 on 198kHz. I live near a medium-wave transmitter by the Ithon river in Llandrindod Wells in Mid-Wales, which provides a strong signal with an external aerial. (I must try a frame aerial wound on an umbrella as in the Japanese Kasa crystal set: **www.kasaradio.com/en/index.html**). Unfortunately, all I could get inside the workshop was switch-mode power supply buzz, so polluted has our RF world become. Even outside, all I got was Radio 5 Live. I suspect the crystal set has now become an unusable historical object. I also suspect human hearing sensitivity has declined due to traffic noise and phone use. With the output of the crystal set in the order of microwatts, most people today just can't hear it.

The circuit shown in Fig.7 couldn't be simpler. All it needs is a parallel tuned circuit and a detector to demodulate the waveform. This is achieved by rectifying the signal; the resulting DC level reflects the modulation or envelope.

To obtain maximum power to feed the crystal set, a long high aerial and a good earth are necessary. If either of these are insufficient then the set won't work at all.

Remember, there is no chance of a ferrite rod alone picking up enough signal for a crystal set – you really do need a long, well-insulated conductor and a good earth to complete the circuit. As a child, I used my bed's metal frame for the aerial. This time, I upgraded to a washing line made with wire and a copper water pipe for the earth, as shown in Fig.8. Another upgrade worth trying is making the aerial's suspension from glass insulators (Fig.9).

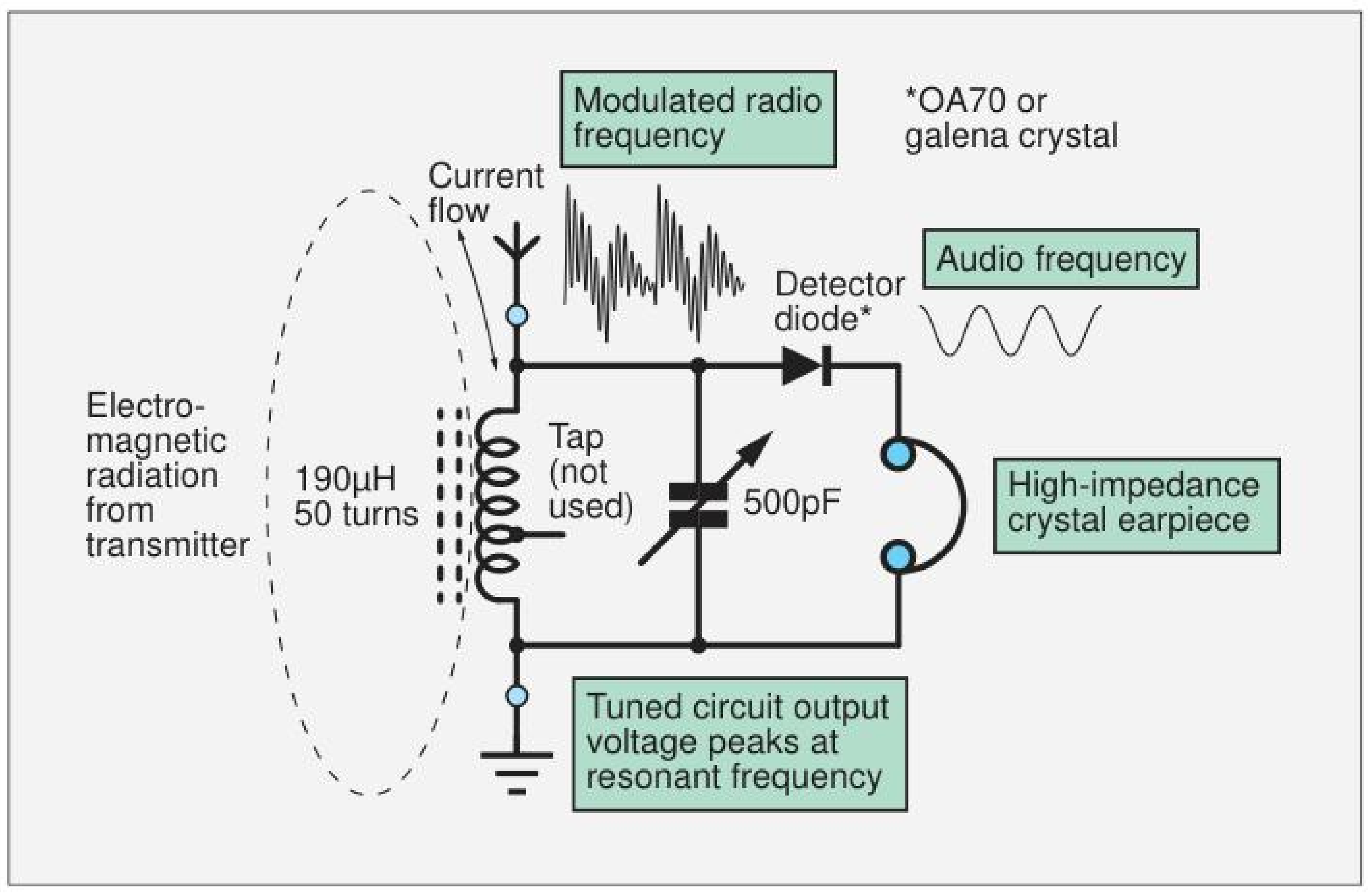
Modulated radio frequency
*OA70 or galena crystal
Current flow
Audio frequency
Detector diode*
Electro-magnetic radiation from transmitter
190µH 50 turns
Tap (not used)
500pF
High-impedance crystal earpiece
Tuned circuit output voltage peaks at resonant frequency

Fig.7. The Ladybird crystal set circuit.

Headphones

The headphones used should be 4k high-impedance balanced-armature types, which have excellent sensitivity. These are very hard to obtain today. A crystal earpiece (Fig.10) can also be used, which is the next best thing and easier to buy. It's an ugly component, looking like a hearing-aid from the 1950s. However, its piezoelectric transducer has high sensitivity and high impedance. So much so that I could hear a click just touching one lead on the ring on my finger (the other held in my other hand). Annoyingly, I couldn't get the thing to stay in my ear without sliding a bit of pink silicone sleeving over it. Also, I found I was completely deaf to very low sound levels in my right ear.

Apparently, there is a more modern type that uses piezoelectric ceramic discs. These transducers also act as a smoothing capacitor for the demodulator, having a capacitance of around 15nF. I also tried a pair of Beyer

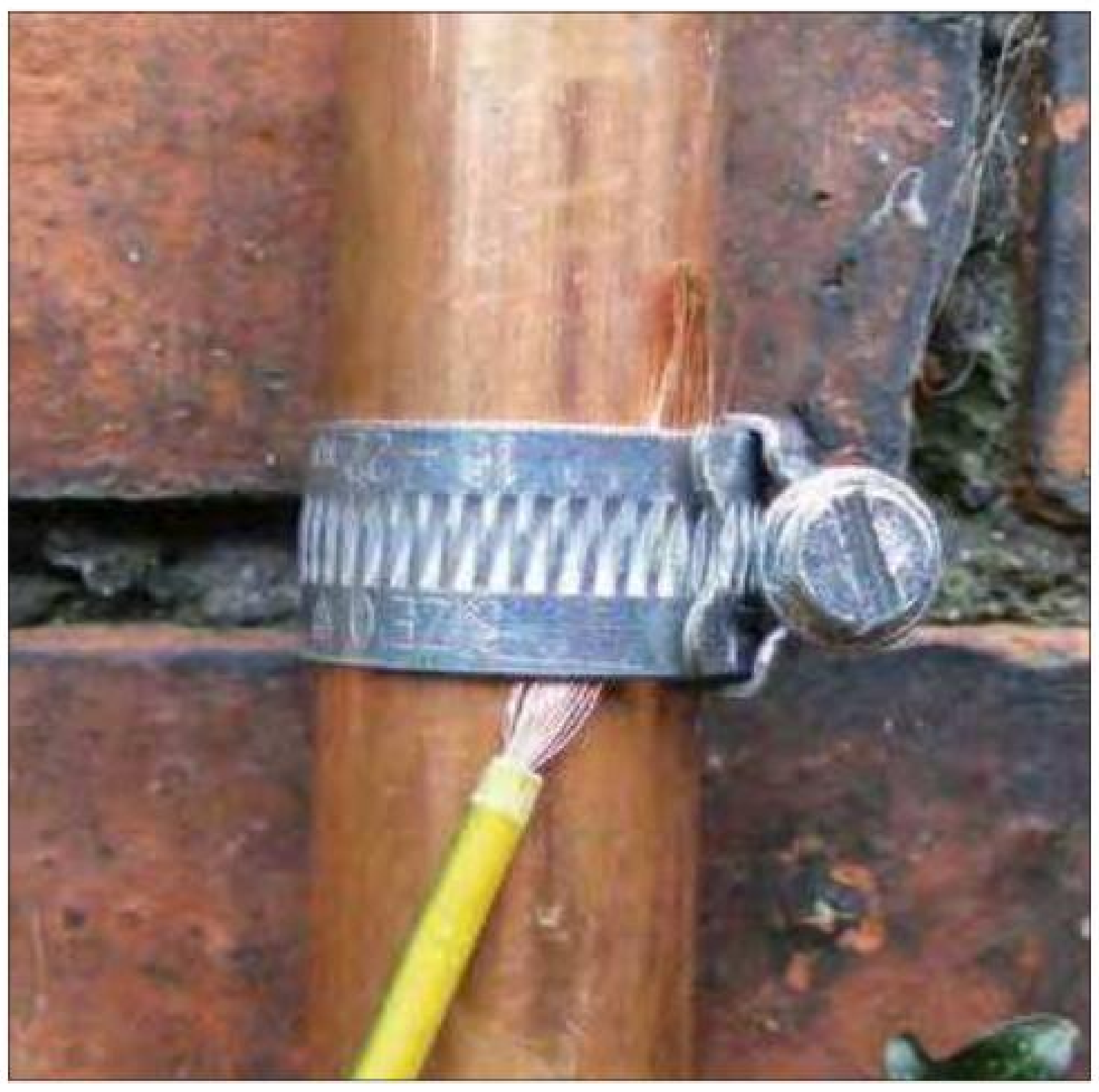

Fig.8. A good earth is needed for a crystal set aerial. Copper water pipes going into the ground are ideal. (Watch out, blue plastic Alkathene pipes are often used for water mains today). Put a steel reinforcing rod into the copper earth pipe if you are going to bang it into hard soil. I used a radiator water pipe as a kid.

Fig.9. A good aerial is vital. A horizontal loop around the picture rail in a Victorian house is good enough to get the crystal set working, but for best results string it up outside as high and long as possible using glass insulators. I found this insulator on the side of a disused railway!

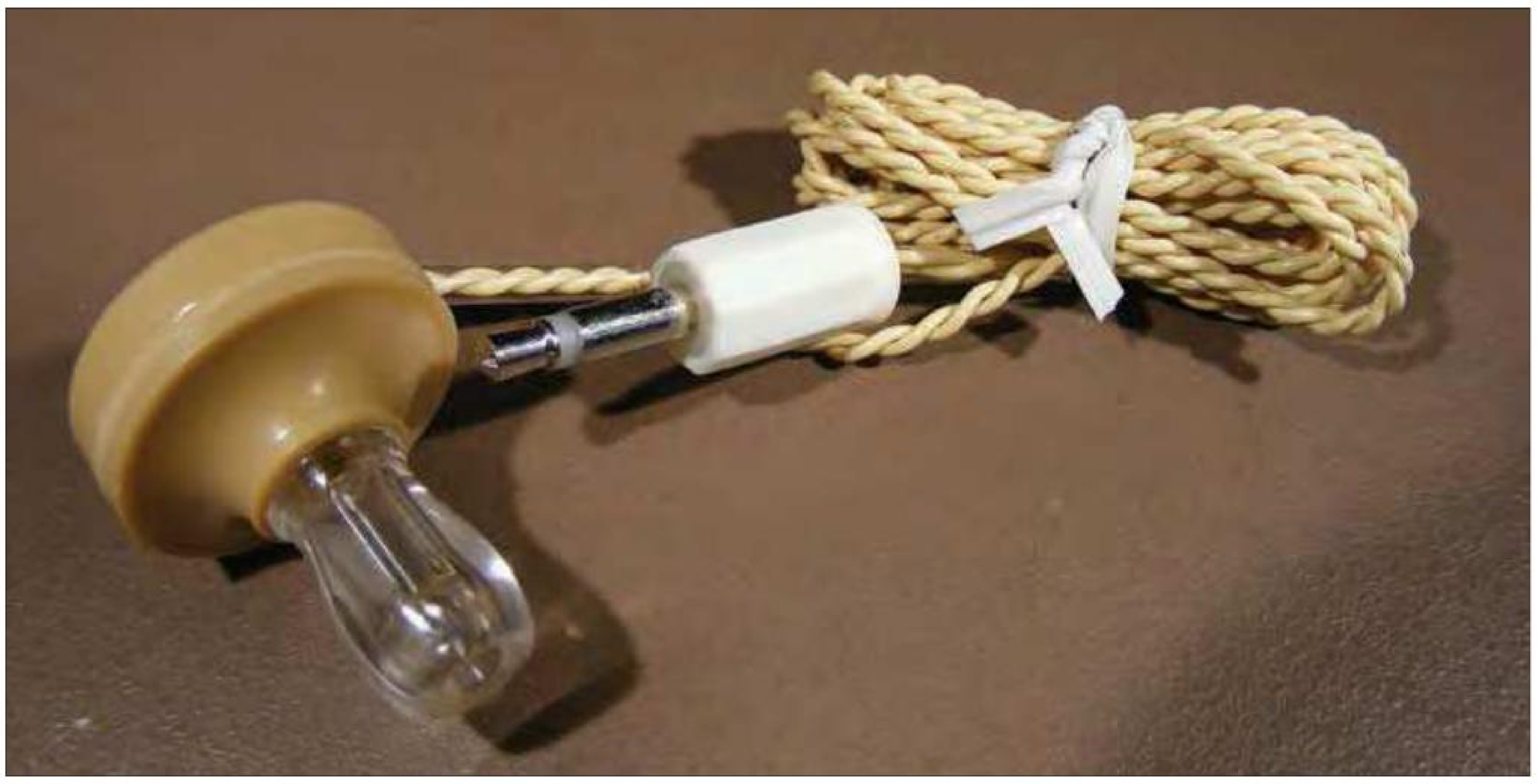

Fig.10. Crystal earpiece – they look awful and sound worse, but do respond to just a few mV.

Dynamic DT100 moving-coil studio headphones of 2kΩ impedance and they were surprisingly *insensitive* and not much use.

Taken prisoner

Crystal sets have a fascinating history as the basis for POW (prisoner of war) radios. Most were based on the crystal set and bits stolen from old telephones. The only 'real' electronic component required was a telephone earpiece, and POW versions of these were possible if you could find magnets and fine copper wire. The tuning capacitor could be a pair of tin cans sliding in and out. The detector was often a galena crystal, basically lead ore or lead sulphide, a natural semiconductor. This mineral, shown in Fig.11, can be found on the ground in my home county of Derbyshire; my friends and I all tried making crystal sets with it.

George Dobbs has a chapter on POW radios in his book and recommended using a piece of coke; I had no luck with this when I tried a lump from the school playground coke heap. (This was before natural gas heating and every school had a pile of coke fuel).

These old detectors were 'point-contact' devices, precursors to the transistor. The point of contact was critical and much poking about was required to get a rectifying crystal boundary. A sharp graphite pencil or springy wire filed to a point works well; oxidised wire does not work at all. Once a suitable spot is found, it has to be held exactly and firmly in position. The wire can be wound into a spring as shown in Fig.12. Interestingly, I found the galena crystal shown in Fig.11 had a very low resistance of around 4Ω when probed on new shiny surfaces. Being a natural mineral, its electrical properties are highly variable. Any particular sample will have different contaminants. The resultant doping action can change the semiconductor from P to N type and sometimes just to a conductor. It is possible to buy selected 'radio-grade' galena crystals. These are generally mounted in a pot of Wood's metal. All crystals can only exhibit diode action at certain contact positions, such as oxidised areas or crystal boundaries. The diode action is often very poor. Measuring the forward voltage drop on a multimeter diode-test function I had 200mV one way and 300mV the other. This provides a degree of rectification and the high reverse leakage stops the capacitive crystal earpiece getting fully charged up, negating the need for a load resistor.

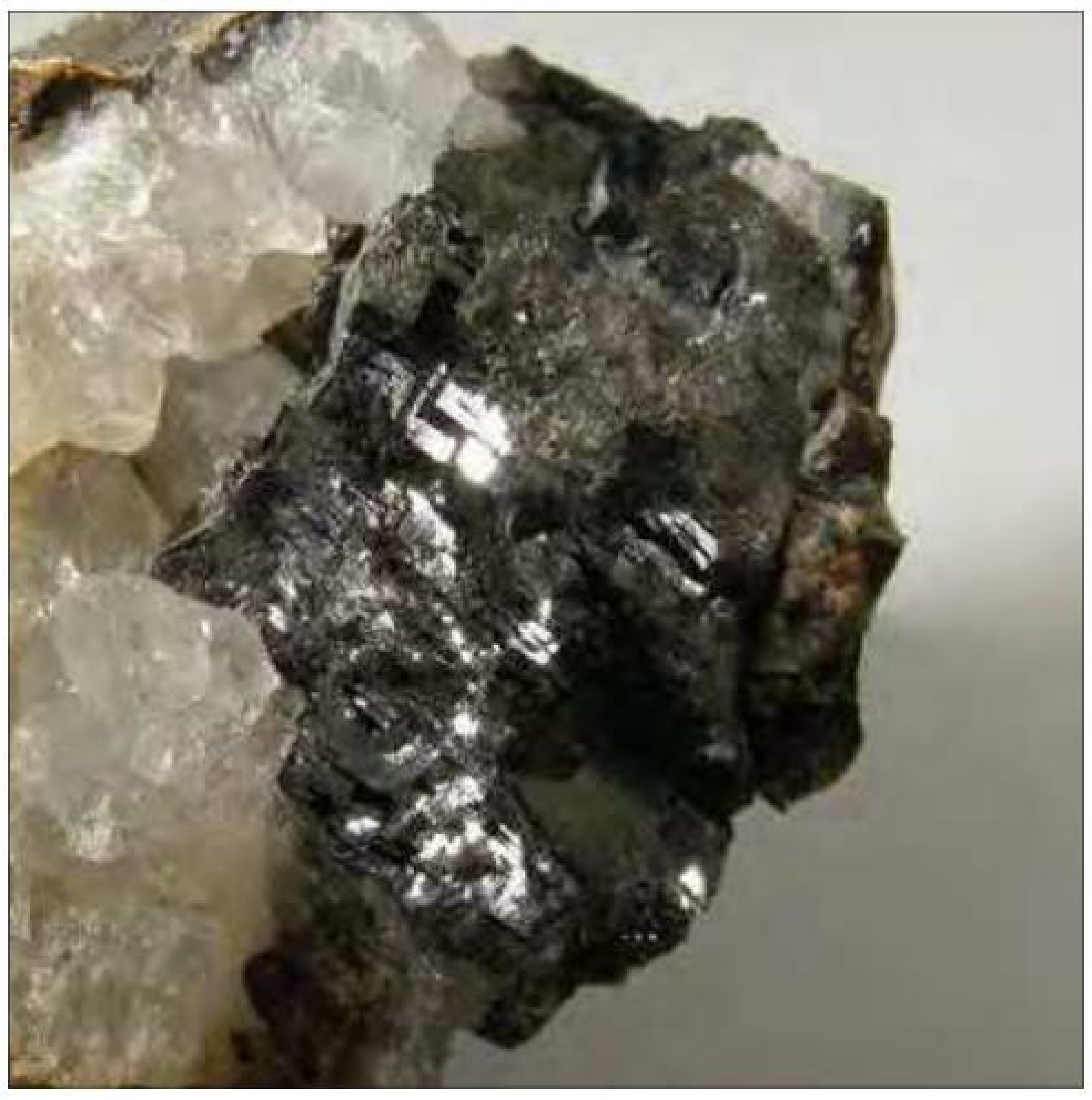

Fig.11. Galena crystals (right) combined with quartz – an electronic hippy's dream.

Real diodes

To get round all this hassle, the germanium small-signal diode was developed. These are the only point-contact semiconductor devices still made. They were also one of the first semiconductor devices to be mass produced, necessary for the Second World War effort. They are usually encapsulated in glass, allowing the crystal and point-contact wire to be clearly seen, as shown in Fig.13. This type was an early STC device. Similar looking OA70s were used in the circuit shown in Fig.6 and Fig.7. Old Siemens OA85 diodes are still available, but they are coated in black paint to stop light increasing the leakage current. The Ladybird design used the OA81 which was very popular in 1960s UK radios. All these big old diodes have the SO-15 case.

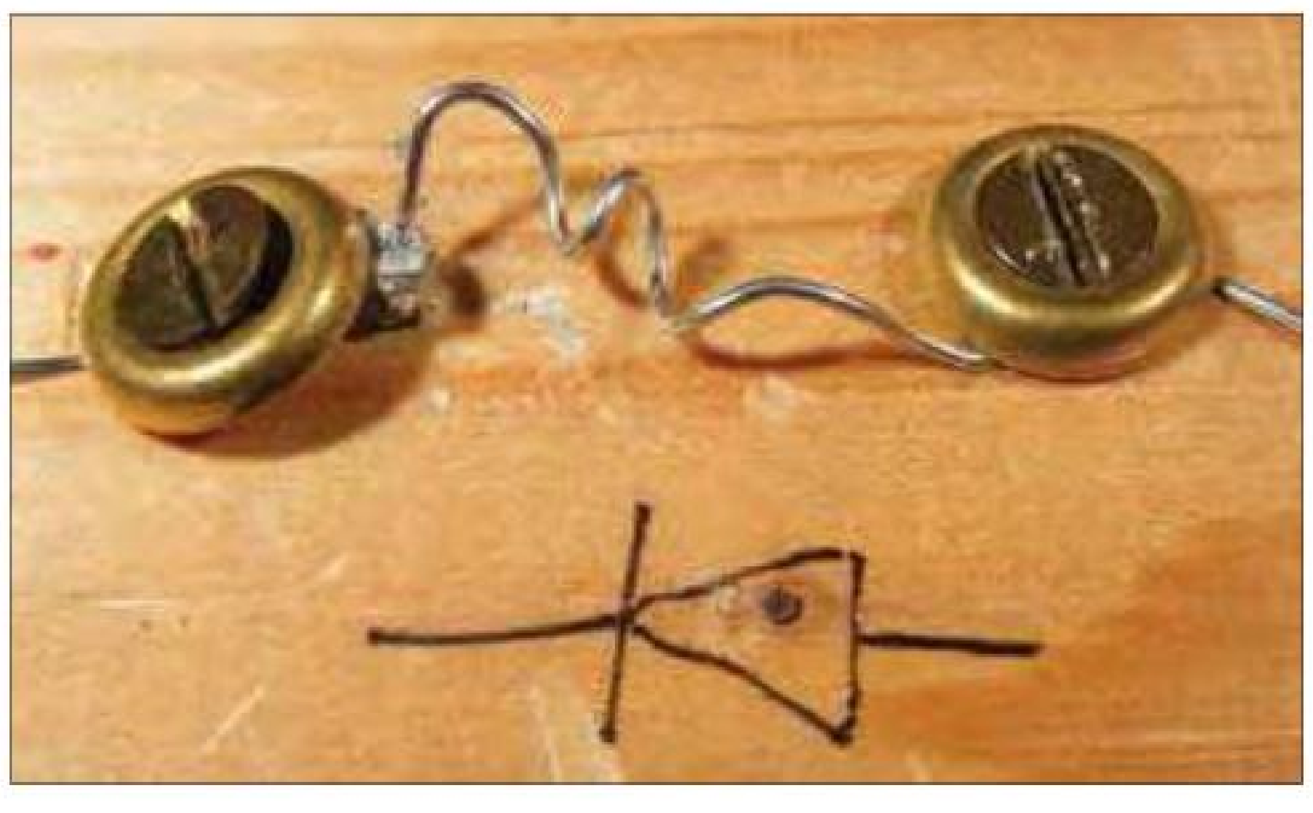

Fig.12. A detector using a galena crystal based on the Ladybird book design. Note the springy pointed wire, sometimes known as a 'cat's whisker'.

There are a few physically smaller types available, such as the OA91, 1N34A and CG92 which will do the job. The OA91 is the OA81 in a DO-7 case. If you can't get a germanium diode, a Schottky type such as an IN60, ZC5800 or BAT42 can work almost as well in crystal sets. After all, it could be argued a galena detector, with its metal-semiconductor junction is a form of Schottky diode. Normal silicon diodes such as the 1N4001 or 1N4148 won't work because of their high forward voltage and sharp knee, although 0.5V of forward bias from a battery will get it to work. The Kasa radio site suggests using an LED and exposing it to light to generate its own bias voltage.

Next month

In the next part we'll get to the heart of the book and build a true transistor radio.

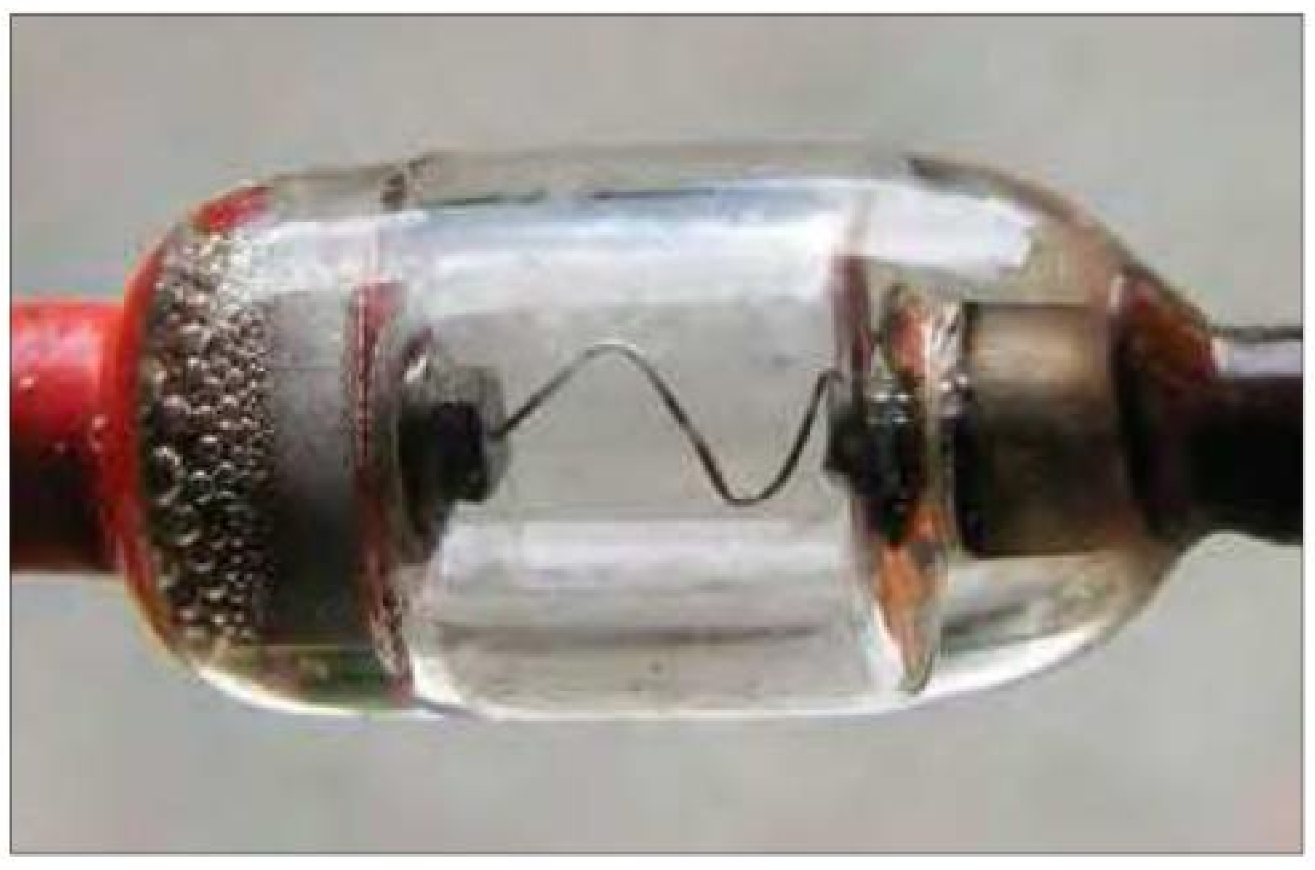

Fig.13. An old germanium point-contact diode. Note the slab of germanium and the spring-loaded point-contact wire.

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Always check price and availability in the latest issue or online. A large number of older boards are listed for ordering on our website.

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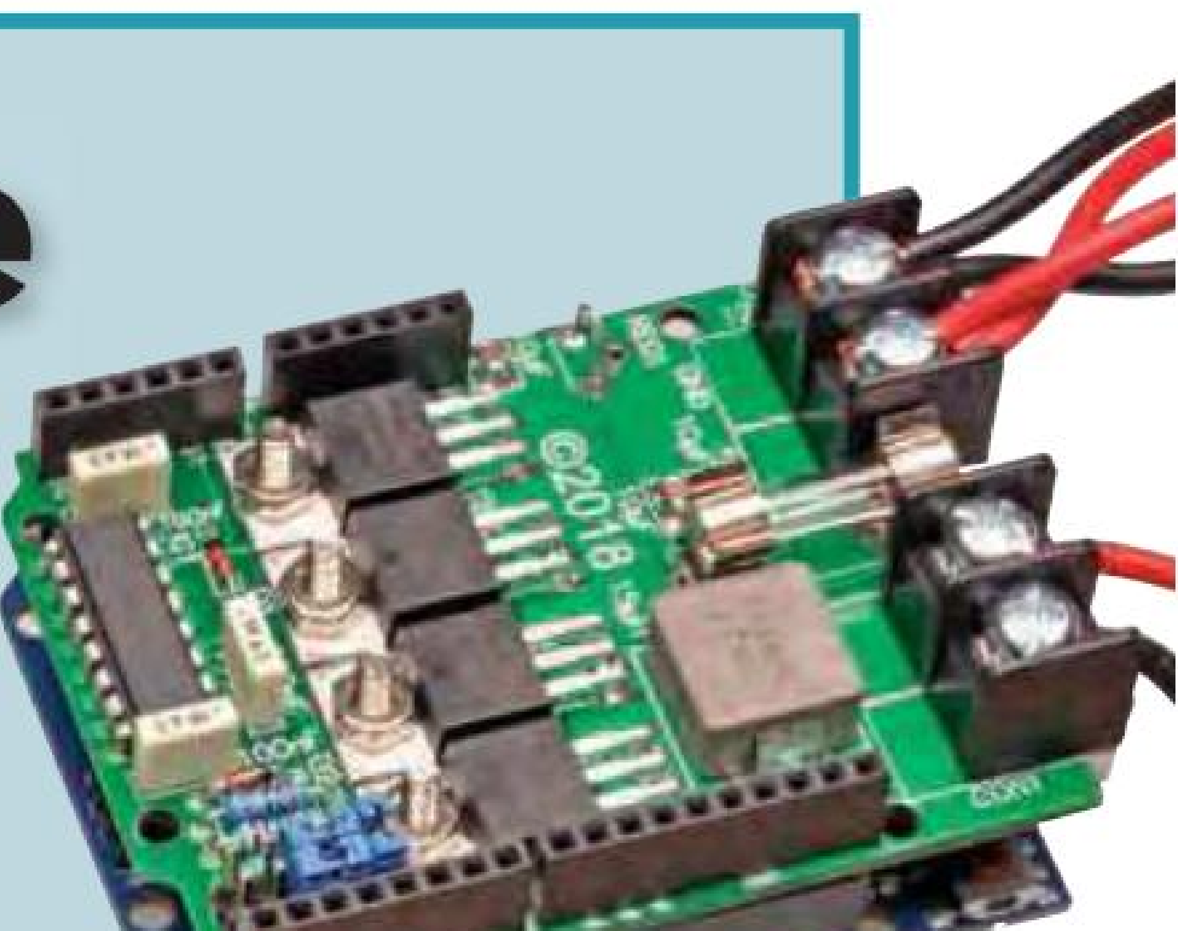
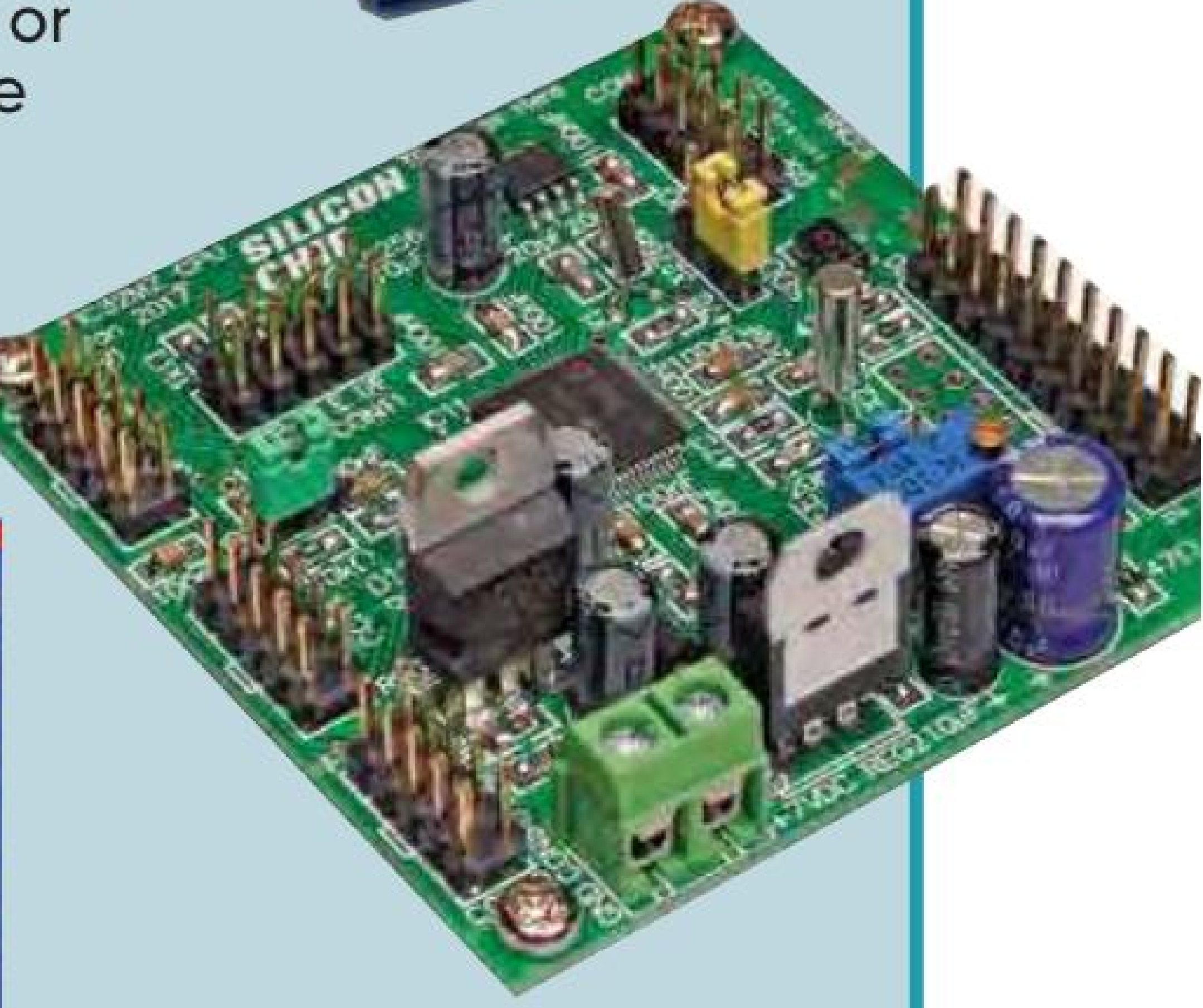
Next Month – in the April issue



Programmable Thermal Regulator – Part 2
Next month, all the instructions describing how to build the two Arduino shields, program the Arduino, build the water loops and tweak it to suit your needs.

DIY Solder Reflow Oven with PID Control – Part 1
Make short work of soldering boards full of surface-mounting components with this low-cost and easy-to-build DIY solder reflow oven. It's quite cheap to build but it runs your PCB(s) through a temperature profile much like a professional reflow setup costing thousands of pounds! It can also be used to 'bake' components, cure glue or paint, or any other task where you need to hold something at a stable, elevated temperature for some time.



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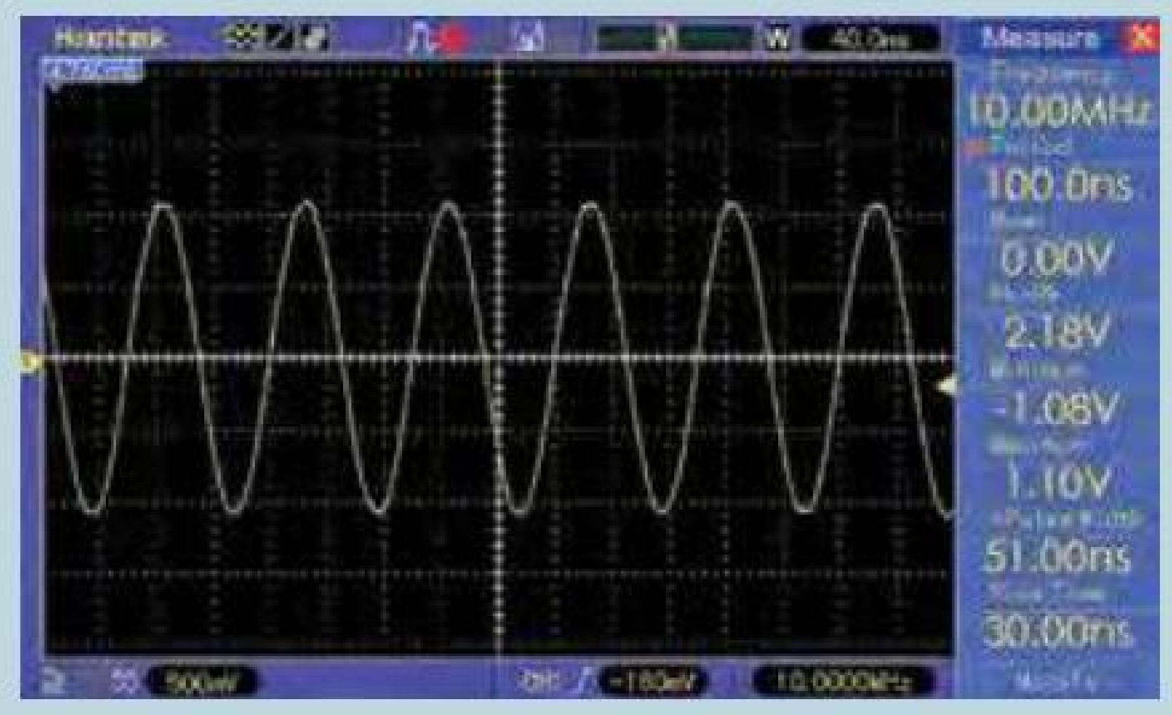

KickStart: Part 2
This second instalment shows you how to use low-cost RFID devices and work with cards and tags. In keeping with the KickStart philosophy, we've provided sufficient information for you to be able to incorporate RFID in your own projects.

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ESR70 Equivalent Series Resistance and Capacitance Meter

Now with backlit display and AAA battery!

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ESR, low resistance and capacitance meter
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It's only possible to show summary specifications here. Please ask if you'd like detailed data. Further information is also available on our website. Product price refunded if you're not happy.

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